Arnold Schwarzenegger
*Governor*

# CATALYTIC COMBUSTOR-FIRED INDUSTRIAL GAS TURBINE

PIER FINAL PROJECT REPORT

*Prepared For:*
**California Energy Commission**
Public Interest Energy Research Program

*Prepared By:*
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Solar Turbines
A Caterpillar Company

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# Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

*Catalytic Combustor-Fired Industrial Gas Turbine—Final Report* is the final report for the Catalytic Combustor-Fired Industrial Gas Turbine project (contract number 500-01-045) conducted by Solar Turbines Incorporated. The information from this project contributes to PIER's Environmentally Preferred Advanced Generation Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

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# Abstract

This report presents the completion of a two-phase project undertaken by Solar Turbines Inc., along with the California Energy Commission, aimed at developing a natural gas-fueled, ultra-low oxides of nitrogen ($NO_x$) emitting industrial gas turbine combustion system. The work focused on a combustion system sized for a 7.5 megawatt (MW) Solar Turbines Taurus 70 (T-70) gas turbine engine. Solar Turbines, Inc. is headquartered in San Diego.

In Phase I, Solar Turbines assessed lean catalytic combustion (technology) with Catalytica Energy Systems Incorporated. After determining that such a system would not be economically competitive against selective catalytic reduction exhaust cleanup systems (SCR), Phase II focused on advancing Alzeta's nanoSTAR™ combustion technology to a proof-of-concept engine test to determine the viability of the technology.

Phase II culminated with the nanoSTAR™ system having undergone testing on a T-70 engine, and a unique recuperated Solar Turbines Centaur 40 (C-40) engine that allowed the same combustion system to be evaluated. T-70 engine tests uncovered the need to improve airflow distribution at the inlet to the fuel-air mixers. At 50 percent load, emissions of $NO_x$ in the T-70 engine did not meet program goals. With the airflow distribution improved at the inlet to the premixers, C-40 engine tests demonstrated sub-3 ppm $NO_x$ emissions with less then 10 ppm carbon monoxide (both corrected to 15 percent oxygen). In both cases, the nanoSTAR™ system successfully met engine operating criteria, including temperature limits and engine transient events such as startup, acceleration, and pilot/main transitions.

Concurrently, Solar Turbines continued to work with Precision Combustion Inc. to advance a rich/lean catalytic system as a third potential candidate technology for an ultra-low emissions gas turbine. This work was funded by the U.S. Department of Energy (DOE).

Of the three technologies evaluated, the nanoSTAR™ system could more readily be adapted to existing T-70 engines. Further work to evaluate durability would require a long-term engine field test.

**Keywords:** Ultra-low, emissions, $NO_x$, CO, surface combustion, porous, catalytic, combustion, rich, lean, premixed, sub-2.5 ppm, gas turbine, nanoSTAR™, RCL, Xonon, combustion system, combustion technology, engine, combustor, injector, burner, mixer, premixer, power generation

# Executive Summary

### *Introduction*

Solar Turbines Inc., headquartered in San Diego, along with the California Energy Commission, has completed a program aimed at developing a natural gas-fueled, ultra-low oxides of nitrogen ($NO_x$) emitting, industrial gas turbine combustion system for the Taurus 70 (T-70) gas turbine. Work for this project was conducted in San Diego, in Mountain View, and in Peoria, Illinois.

### *Purpose*

This project was to advance a sub-2.5 parts per million (ppm) $NO_x$ combustion technology for the T-70 industrial gas turbine. A complete prototype combustion system was to be designed, procured, and evaluated at Solar Turbines. Testing was to culminate in an engine evaluation. Successful development of one or more of the combustion technologies evaluated has the potential to lower costs for and increase market demand and penetration of ultra-low emissions industrial gas turbines that are used in distributed generation (that is, electricity production that is on-site or close to a load center and is interconnected to the utility distribution system). The research supports PIER Program objectives in the areas of:

- Improving the energy cost/value of California's electricity by reducing the electric power costs for the public and private sectors, increasing the electric capacity within the state, and enhancing the state's power infrastructure.
- Improving the environmental and public health costs/risk of California's electricity by reducing emissions from gas turbines and through the creation of superior $NO_x$ reduction technologies.

### *Project Objectives*

The program had the following technical objectives:

- Maintaining $NO_x$, carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions below 2.5 ppm, 10 ppm, and 10 ppm (at 15 percent oxygen [$O_2$]), respectively.
- Meeting these emissions goals over an engine load (that is, engine power output) range of 80 to 100 percent of maximum.
- Demonstrating that the system components operated below the design temperature limit (1650° F) for good service life.

The economic objective of the project was to develop a combustion technology that costs less than current selective catalytic reduction (SCR) systems.

### *Project Outcomes*

Three ultra-low $NO_x$ technologies were evaluated to accomplish the program goal:

- Catalytica Energy Systems Incorporated's (CESI) lean catalytic combustion system that uses a catalytic reactor module to operate at very low flame temperatures where $NO_x$

formation is minimal. This technology had progressed under earlier Energy Commission and U.S. Department of Energy (DOE) contracts. A successful demonstration on a 1-megawatt (MW) turbine had been completed. Phase I of this program would scale the system to larger engines and higher operating temperatures.

- Alzeta's nanoSTAR™ surface combustion system, which allows combustion at lower temperatures resulting in lower $NO_x$ emissions. Earlier burner rig testing had been conducted with both Energy Commission and DOE support. Alzeta is based in Santa Clara.
- The rich/lean, two-stage catalytic combustion concept of Precision Combustion Incorporated (PCI), where an initial, fuel-rich combustion stage is stabilized catalytically. This is followed by a second lean burnout step. This technology was the least developed of the three but had shown very low $NO_x$ levels in DOE-supported single-burner rig tests. Precision Combustion is based in North Haven, Connecticut.

The program was structured in two phases. At the end of Phase I, although the CESI technology met emissions and short-term durability targets in tests, the technology was judged to be too costly to warrant commercialization, and further development stopped. Major cost factors included the catalytic reactor, new engine housings, and external packaging structures required to adapt the T-70 to a side-mounted can combustion system. Operating costs were high due to the need to replace the catalytic reactor on a one- to two-year schedule to maintain emissions performance.

Phase II focused on the engine evaluation of the Alzeta nanoSTAR™ surface combustion technology. An axial combustor configuration, using existing burners and fuel-air premixers, was chosen to undergo evaluation in an existing T-70 engine. The configuration sacrificed the ability to remove injectors in the field for a more near-term test of burner durability, engine control feasibility, and emissions performance. Concurrently, although with funding from the DOE, Solar Turbines worked with PCI to evolve the rich/lean, two-stage catalytic technology for appropriate full-scale evaluations.

### *Conclusions*

Engine tests completed in this program with the Alzeta nanoSTAR™ combustion system have shown promising results. With emissions of around 3 ppm $NO_x$ and less than 10 ppm CO, its performance has been second to the catalytic systems, which have shown around 1 ppm $NO_x$ and less than 10 ppm CO. However, the nanoSTAR™ technology has shown great promise in terms of engine adaptability. Integration into a T-70 gas turbine would require the lowest level of production hardware modifications. A lower impact on the production engine configuration translates to reduced cost, risk, and development time.

Engine tests of the nanoSTAR™ system have demonstrated excellent short-term durability under real engine conditions. The system has consistently met engine operating criteria during engine tests, including temperature limits and performance during startup, acceleration, and pilot/main transitions. These milestones were accomplished without any measurable hardware degradation. Of the three ultra-low emissions technologies assessed, the nanoSTAR™ technology is best positioned for integration with existing T-70 engines.

### *Recommendations*

Further work to assess long-term durability is required to declare the technology market-ready. Concerns about plugging, mechanical vibrations, and fuel impurity effects would be best addressed in field evaluations. After developing adequate field-ready premixers, the next logical step for the evolution of this technology would be a long-term engine field test.

### *Benefits to California*

Commercialization of ultra-low $NO_x$ combustion technology will accelerate the growth of distributed power generation and cogeneration in California by providing a lower-cost alternative to exhaust gas cleanup (selective catalytic reduction systems). It may also lead to:

- Reductions in the cost of electricity by helping expand/enhance the state's power infrastructure.
- Reductions in environmental and public health risks by reducing harmful gas turbine emissions.

# 1.0 Introduction

This report presents the results of a project conducted by Solar Turbines in collaboration with the California Energy Commission to develop a natural gas-fueled, ultra-low $NO_x$, industrial gas turbine combustion system. The $NO_x$ emissions goal for the combustion system, sub-2.5 ppm $NO_x$ (at 15% $O_2$), was based on emissions regulations that have been adopted in several AQMDs within California. Although these ultra-low $NO_x$ levels can be reached with commercial exhaust gas cleanup systems, it was projected that achieving ultra-low $NO_x$ with an advanced combustion system would be more economical and environmentally friendly.

Initially, the project focus was on Solar Turbines' Taurus 60 (T-60) gas turbine (5.2 MW). However, an updated market assessment motivated a shift from the T-60 turbine to the Taurus 70 (T-70). The Taurus 70 had recently been introduced as a new Solar Turbines product at that time. Because of its larger size, the T-70 (7.5 MW) was deemed to have better market potential for the ultra-low $NO_x$ (ULN) combustion technology.

The project was performed in two distinct phases. In the first phase, Solar Turbines collaborated with Catalytica Energy Systems Incorporated (CESI) in an assessment of CESI's lean catalytic combustion technology for industrial gas turbines. The outcome of Phase I was the conclusion that lean catalytic combustion was not an economically attractive alternative compared to existing exhaust gas $NO_x$ reduction systems (selective catalytic reduction).

Phase II, therefore, proceeded as a collaborative effort between Alzeta Corporation and Solar Turbines to apply Alzeta's ultra-low $NO_x$ surface combustion technology for gas turbine applications. Alzeta's nanoSTAR™ combustion technology was being developed in an Energy Commission project (500-01-0010) in parallel to the Phase I effort of the Solar Turbines project. Solar Turbines had collaborated with Alzeta in the parallel program in the early development of surface combustion for gas turbines. Thus, the transition from lean catalytic combustion in Phase I to the nanoSTAR™ technology in Phase II was relatively seamless.

## 1.1. Background

Over the last twenty years, the gas turbine has come to be recognized as the preferred means of generating electric power in the United States. Gas turbines have a number of attributes that make them attractive relative to coal-fired central power stations and large diesel generators. Among these advantages are: good efficiency in combined cycle and cogeneration applications, low emissions, low cost, short time-to-construct, and ease of maintenance.

Despite the advantages of the gas turbine, the use of turbines in California has been restricted by the unique air quality challenges of the State. The promulgation of strict air quality regulations has required many turbine operators to install exhaust gas cleanup systems. The need for a California-based turbine to have $NO_x$ emissions below 2.5 ppmv is not uncommon. The reduction of $NO_x$ emissions to these levels (from more typical levels of 25 ppmv) is expensive and increases the cost of electricity generated by turbines. The cost impact of exhaust gas cleanup on small and medium sized-turbines (approximately < 25 MW) is more severe (on a $/kw basis) than large turbines because of the "economy of scale" effect.

One approach to lowering the cost of electricity for California residents is by lowering the cost of meeting the State's strict gas turbine emissions regulations. For small and medium-sized gas turbines, advanced combustion technology represents a promising approach to achieving low $NO_x$ emissions levels cost-effectively. Such a cost reduction is expected to spur the use of turbines in California for distributed power generation and cogeneration. The benefits of these turbine applications are widely recognized and include:

- Reduced electricity costs
- Improved fuel use efficiency
- Reduced generation of greenhouse gases (lbs of $CO_2$/MW output)
- Enhanced reliability of the State's power infrastructure

## 1.2. Overview

### *1.2.1. Prior Work*

In an earlier Energy Commission-funded program (Contract 500-098-041), Solar Turbines and CESI collaborated in a design study to identify the best approach to integrate CESI's catalytic combustion technology into a mid-sized industrial gas turbine.

Assessments were made of three combustion system configurations (single can, multi-can, and annular). A combination of technical issues, product cost projections, and development risk assessments led to the selection of the single can system as best for Solar Turbines' products. The primary factors leading to this selection included:

- CESI's extensive background in cylindrical catalytic system design, manufacture and test. Conversely, a lack of experience with annular combustion systems.
- The existence of preburner, premixer, reactor and burnout zone (BOZ) designs for a can combustor system. These designs could be extrapolated to larger size with less technical risk.
- The geometric simplicity of a single can system relative to the annular and multi-can designs. The simplicity would result in lower product cost.
- The ease of control of a single can system compared to the multi-can system since only one preburner/premixer module was required.

In this earlier program, the T-60 had been selected as the preferred engine for initial development. Shortly into the project, however, Solar Turbines introduced a new product, the T-70. Updated market projections looked more favorable for the larger T-70. Consequently, the program focus shifted from the T-60 to the T-70 with minimal program impact. The commonality of design between the T-60 and T-70 allowed use of the same combustion system configuration for both engines.

Although the single can system was selected, there were two major negative issues associated with it. First, the single can combustor would be replacing an annular combustor. The size and orientation (side-mounted) of the catalytic can combustor would require a major redesign of the engine combustion section. Second, a geometrically complex scroll section would need to be developed to duct the combustor exhaust gases to the engine turbine section. As the scroll experiences the highest temperatures in the gas turbine cycle (combustor exhaust temperature), scroll durability becomes a potential issue. A successful scroll design needs to have adequate cooling to keep wall temperatures and thermal stresses low, as well as producing acceptable inlet flow characteristics (velocity and temperature) to the turbine section. With the large amount of air required by the catalytic reactor, there is little air (by conventional standards) left to accomplish scroll cooling.

### 1.2.2. Project Scope: Phase I

Phase I of this project was a collaborative effort with CESI to develop a catalytic combustion system for industrial gas turbines. The work involved the detailed design and fabrication of a full-scale catalytic can combustion system for the T-70 engine. A series of rig tests were conducted to evaluate and optimize the individual system components, specifically the preburner/premixer, and catalytic reactor. Subsequently, the combustion system was assembled and rig tested at both atmospheric and high pressures. The high-pressure combustion rig tests were conducted at the Caterpillar Technology Center (CTC) in Peoria, IL where high airflow test facilities are available.

In parallel with the Phase I testing, catalytic system cost estimates (including engine modifications) were developed to support assessments of commercial feasibility. Projected product capital and operating costs were compared to similar costs for SCR technology.

The Phase I CTC testing demonstrated the ability of CESI's catalytic system to achieve $NO_x$ emissions below 2.5 ppm on natural gas. However, the cost assessments indicated that the catalytic system was not economically competitive with existing SCR technology. The cost factors of greatest significance were the recurring costs for catalytic reactor replacement and the cost of the combustor scroll. Consequently the Phase I effort concluded with the decision to suspend any further development of the CESI system for Solar Turbines' product line.

### 1.2.3. Project Scope: Phase II

In Phase II, the program focus shifted to Alzeta's nanoSTAR™, non-catalytic, surface combustion technology. Phase II continued the nanoSTAR™ technology development started in earlier projects supported by the California Energy Commission. The immediate predecessor program to the current program (500-01-0010) culminated in the rig testing of a full-scale nanoSTAR™ combustion system at the CTC. The system's ultra-low $NO_x$ capability was demonstrated at simulated T-70 operating conditions.

The intent of Phase II of the current program was to advance the nanoSTAR™ combustion Alzeta system to T-70 engine testing at Solar Turbines – the first test of the surface combustion technology on a medium-sized, production gas turbine.

## 1.3. Project Objectives

The objective of this project was to advance a <2.5 ppm $NO_x$ combustion technology for the T-70 industrial gas turbine. A complete prototype combustion system was to be designed, procured, and evaluated at Solar Turbines. Testing was to culminate in an engine evaluation.

On a broader scale, the objective was to demonstrate that ultra-low $NO_x$ combustion technology is a viable option for California-based turbines to meet the State's strict $NO_x$ emissions regulations. The commercialization of such a technology will accelerate the growth of distributed power generation and cogeneration in the State by providing a lower cost path to ultra-low $NO_x$ compared to exhaust gas cleanup.

The project supported the PIER program objectives of:

- Reducing the cost of electricity in California and expanding/enhancing the State's power infrastructure
- Reducing environmental and public health risks in California by reducing emissions from gas turbines

### 1.3.1. Specific Technical and Economic Objectives

This project had a number of specific technical objectives associated with the integration of an ultra-low $NO_x$ combustion system into the T-70 turbine. These included:

- Maintaining $NO_x$, CO and UHC emissions below 2.5 ppm, 10 ppm, and 10 ppm (at 15% $O_2$), respectively
- Meeting these emissions goals over an engine load a range of 80 to 100%
- Demonstrating that the system components operated below the design temperature limit (1650°F) for good service life

The economic objective of the project was to develop a combustion technology that was lower cost than current SCR systems. This translated into keeping the incremental cost (mils/kWh) of owning and operating the combustion system to less than 20% of current turbine-based electric costs.

### 1.3.2. Technology Down-Select

A unique element of this program was the opportunity for Solar Turbines to select, from three unique ultra-low $NO_x$ technologies, the best system to take to engine testing. As lean catalytic combustion was advancing in Phase I, two other technologies were being moved forward in separate projects. The "down-select" to the best technology was envisioned as either a one-step or two-step process depending on the rate of technical progress. The down-select was to consider technical and commercial issues as well as development risk.

The technology candidates included:

- CESI's lean catalytic combustion system that uses a catalytic reactor module to operate at very low flame temperatures where $NO_x$ formation is minimal. This technology had progressed under earlier Energy Commission and DOE contracts. A successful demonstration on a 1 MW turbine had been completed. Phase I of this program would scale the system to larger engines and higher operating temperatures.
- Alzeta's nanoSTAR™ surface combustion system; where a lean-premixed flame is supported on the outside of a porous metal cylinder. Improved stability allows

combustion at lower temperatures and with lower $NO_x$. Earlier burner rig testing had been conducted with both Energy Commission and DOE support.

- The rich/lean, two-stage catalytic (RCL) combustion concept of Precision Combustion Incorporated (PCI) where an initial, fuel-rich combustion stage is stabilized catalytically. This is followed by a second lean burnout step. This technology was the least developed of the three but had shown very low $NO_x$ levels in DOE-supported single burner rig tests.

At the end of Phase I, the CESI technology was assessed as too costly to warrant commercialization. Phase II, therefore focused on the nanoSTAR™ system. At the same time, the RCL system was still under-going single burner rig testing in a DOE program.

## 1.4. Results Summary

Phase I and Phase II results are summarized in the sections below.

### *1.4.1. Phase I: Lean Catalytic Combustion (CESI)*

In Phase I, the CESI catalytic combustion technology was successfully adapted for use on a T-70 gas turbine. A single-can combustion system was selected as the most practical configuration for the T-70. The combustion system included a preburner, a fuel/air premixer, the catalytic reactor module and a burnout zone. A prototype design of such a system was completed. Hardware was fabricated, and rig tests were conducted to verify the performance of the individual components.

Subsequently, the entire combustion system was assembled for rig testing at simulated T-70 conditions. The testing established the ultra-low $NO_x$ capability of the CESI system with $NO_x$ emissions near 1ppm and CO below 10 ppm on natural gas operation. All aspects of the combustor performance were deemed satisfactory, and no short-term durability issues were uncovered.

An assessment of the development risk associated with the catalytic system suggested that the scroll section located between the burnout zone (BOZ) and the turbine nozzle was the highest risk component. This component was not required for the rig testing conducted in this program. However, conceptual designs of the scroll indicated that scroll cooling would be a major challenge in the development of a durable part.

Production cost estimates of the catalytic combustion system indicated that the technology would not be cost-competitive with existing SCR systems. Major cost factors included the scroll, the catalytic reactor, new engine housings, and external packaging structures required to adapt the T-70 to a side-mounted can combustion system. Operating costs were high due to the need to replace the catalytic reactor on a one-to-two year schedule to maintain emissions performance.

Although the CESI combustion system met the technical goals of the program, its commercial feasibility was considered low. As a result, work on this system within this program was stopped at the end of the Phase I. CESI subsequently made a business decision to license its catalytic combustion technology to others.

### 1.4.2. Phase II: Surface Combustion (Alzeta)

In Phase II, the Alzeta surface combustion technology was successfully adapted for use in the first ever T-70 gas turbine engine tests. While the same burners and fuel-air premixers developed in a previous contract were used, a new annular combustor was developed to maximize the volume available for CO burn-out. The combustor size was increased to the maximum extent possible without modifying the production T-70 pressure casing.

Tests on the in-house T-70 engine concluded with encouraging results. Smooth engine light-off and acceleration to 50% load, and transitions between pilot and main-stage operation were demonstrated repeatedly. Measurements of combustor metal temperatures, dynamic pressure fluctuations, and combustor exit temperature uniformity all met established engine specifications. However, emissions performance at 50% load fell short of the project goals—$NO_x$ measured at 13 to 15 ppm. In addition, testing at higher loads was not possible due to a suspected air leak within the engine and not associated with the combustion system. Overall, tests on the T-70 engine were successful at demonstrating:

- Adequate component temperatures, and combustor exit gas temperature distribution
- The ability of surface combustion system to handle transient engine operation without suffering any damage
- An engine control algorithm to enable smooth and safe engine operation; including transient and steady-state operation from light-off and acceleration, to the transitions of pilot and main-stage operation

These first engine tests also served to highlight the importance of improving the airflow uniformity at the inlet of the fuel-air premixers. Analyses showed that the quality of fuel-air mixing provided by the proof-of-concept engine premixers was very sensitive to the (combustor) plenum air distribution. Once this sensitivity was reduced, subsequent tests on a recuperated C-40 engine (equipped to use the same T-70 combustion system tested above) demonstrated 3 ppm $NO_x$ emissions with less than 10 ppm CO at simulated T-70 full-load temperature.

The success of the axial (in-line) combustion system engine evaluations, and the significant efforts associated with developing a canted combustor system, spurred further interest on an axial nanoSTAR™ combustion system. The next-generation design would seek to employ a more compact premixers that would:

- Reside further away from the compressor diffuser, where the air flow field is more uniform, and be less sensitive to poor airflow distribution
- Be small enough to allow retrofit into existing T-70 engines

A premixer that meets the above criteria would allow the surface combustion system to be adapted on existing engines without costly changes, and thereby facilitate field assessments. Such assessments are still necessary to prove out long-term durability. In the end, decreasing the level of modifications required to adapt the new combustion system to existing engines should reduce costs and risks, and improve product marketability—important attributes for this technology that to date continues to provide emissions 1 to 2 ppm higher than the catalytic systems.

## 1.5. Production Readiness/Commercialization

The production readiness plan completed in Phase II found no manufacturing issues that would impede commercialization of the nanoSTAR™ technology. This plan concentrated on the surface burner components that would be manufactured by Solar Turbines. These parts can be produced by Solar Turbines (or Solar Turbines suppliers) without the addition of new or expanded facilities and with Solar Turbines' current workforce.

Solar Turbines' sourcing plan calls for purchasing the surface burner elements from Alzeta. Solar Turbines would manufacture the premixer and support hardware. Final assembly of the components into a burner module would be completed by Solar Turbines.

Alzeta has addressed their production readiness in a report provided under a separate Energy Commission contract (500-01-0010). Alzeta believes it has the facilities and processes in house to manufacture burner elements on a production basis as the nanoSTAR™ technology is introduced. Scale-up to meet growing demand is not seen as requiring major capital investments, or as being burdensome to the business.

For the T-70 nanoSTAR™ system to emerge as a product, several remaining tasks must be completed:

- Development of an improved, smaller premixer that allows the burner modules to be removed from the engine in the field
- A detailed design review of the burner components to identify cost reduction opportunities
- A long duration field trail (8000 hour minimum) to demonstrate system durability, emissions and fouling resistance
- Verification of production costs estimates and Alzeta pricing
- Definition of a quality control process to assure consistency in burner performance.

# 2.0 Project Approach

The approach outlined below was followed to develop the natural gas-fueled, ultra-low $NO_x$, industrial gas turbine combustion system. Details about each of the steps taken, and the results obtained are detailed in subsequent sections of this report.

The project was broken into two phases:

1. Phase I was dedicated to the full-scale development and subsequent rig evaluation of one of three candidate ultra-low emissions technologies (CESI's lean catalytic combustion)
    a. The system was designed
    b. The system was fabricated
    c. Components from the system were rig tested
    d. The system was evaluated in full-scale rig tests
    e. The combustion system was subjected to an assessment of: emissions capabilities, durability, system integration, manufacturing status, and projected costs. This information was compared against competing technologies to determine which system would be evaluated on subsequent engine tests.
2. Phase II was dedicated to the engine evaluation of the selected candidate ultra-low emissions technology (Alzeta's surface combustion)
    a. The engine system was designed
    b. The engine system was built
    c. Components and the system were rig tested
    d. The system was tested on a T-70 engine
    e. The engine system was optimized
    f. Optimizations were validated through additional engine tests in a C-40 engine
    g. The combustion system was subjected to an assessment of: emissions capabilities, durability, system integration, manufacturing status, and projected costs. This information was compared against competing technologies to select which system would be recommended for further advancement.

Upon completing the two phases, detailed assessments revealed the preferred technology for an ultra-low $NO_x$ T-70 gas turbine combustion system.

# 3.0 Phase I Project Results: Lean Catalytic Combustion

Phase I included all the project work beginning with design of the CESI catalytic system and ending with the completion of the full scale rig tests of the system at CTC. The effort corresponded to Tasks 2.1 through 2.4 of the contract Statement of Work. The most significant results are presented below.

## 3.1. Catalytic Combustion System Design (Task 2.1)

### *3.1.1. Product specification (Subtask 2.1.1)*

A preliminary Product Specification has been developed to define the performance requirements and product features of the ultra-low $NO_x$T-70 gas turbine. In many aspects, the Product Specification is similar to that of the current T-70 gas turbine. The primary changes related to emissions requirements. Table 1 sets forth the emissions-related specifications for the new turbine product.

**Table 1. Emissions and Operational Range Requirements**

| Engine Parameter | Power Generation (Gas Only Engine) | Oil &Gas Gen Set (Gas Only Engine) |
|---|---|---|
| $NO_x$ (ppm @15% $O_2$) | 2.5 | On-Shore<br>5 Initial<br>2.5 Final |
| | | Off-Shore<br>N/A |
| CO (ppm @15% $O_2$) | 10 | 10 |
| UHC (ppm @15% $O_2$) | 10 | 10 |
| Smoke:<br>Opacity (%)<br>Bacharach | <br>0<br>2 | <br>0<br>2 |
| Low Emission Engine Operating Range | 50 to 100% load | 50 to 100% load |
| Low Emission Ambient Conditions:<br>T1<br>Relative Humidity<br>Barometric Pressure | <br>0 to 120F<br>0 to 100%<br>8000 ft altitude | <br>0 to 120F<br>0 to 100%<br>8000 ft altitude |

### 3.1.2. Catalytic Module Design (Subtask 2.1.2)

CESI led the design development of the T-70 reactor module based on their proprietary technology base. The design reflected an extrapolation of the reactor design developed for use on a 1 MW Kawasaki gas turbine. The T-70 reactor was larger in size and designed for the more severe operating conditions of the T-70 (higher combustor operating pressure and inlet temperature).

The module design required close collaboration between CESI and Solar Turbines to ensure that the module interfaced properly with the other components of the T-70 combustion system. The module included the reactor core and the containment device housing the core (Figure 1).

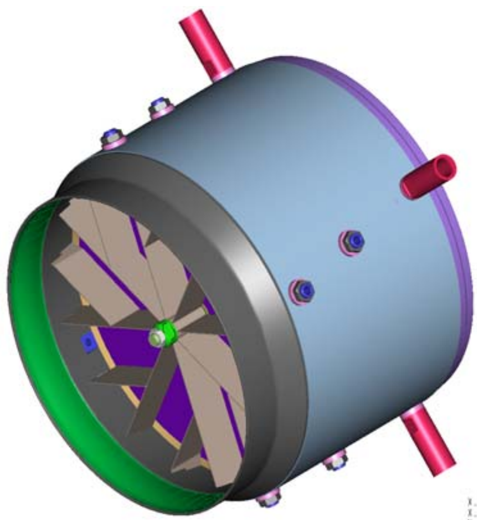


**Figure 1. Taurus 70 Catalytic Reactor Module**

### 3.1.3. Combustion System Design (Subtask 2.1.3)

As the catalytic module design advanced, designs of the other combustor components were developed (Figure 2). These components included the preburner, fuel/air premixer and burnout zone. As with the reactor module, these component designs relied heavily on the prior experience of CESI. Appendix I-A presents detailed descriptions of the preburner, a critical element in the emissions performance of the system.

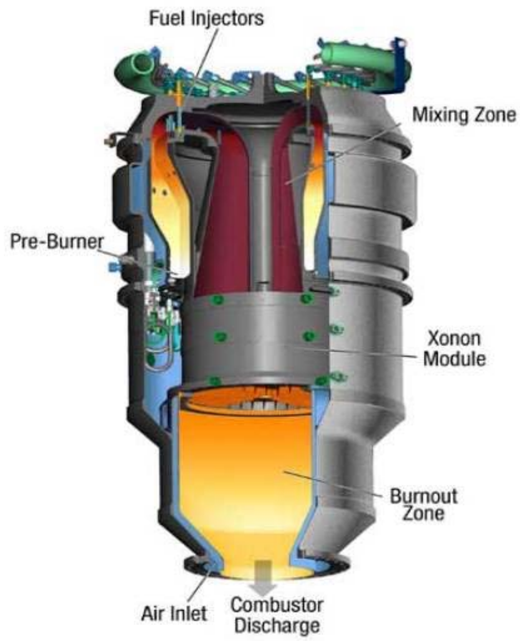



**Figure 2. Taurus 70 Catalytic Combustor Cross-Section**

### *3.1.4. Package/Scroll Definition (Subtask 2.1.6)*

To assess the impact of integrating the catalytic combustion system into the T-70, a preliminary design of the new engine was developed. This conceptual effort served to establish the engine and package modifications that would be required and to develop budgetary cost estimates for the product.

Figure 3 illustrates the production, low emissions T-70 engine configuration. The engine uses an annular combustion system with 12 fuel injectors. For comparative purposes, the cross-section of the side-mounted catalytic can combustion system is shown in Figure 4. It is evident from Figure 4 that the catalytic system results in a major change to the engine profile and will require a significant redesign of the engine center section.

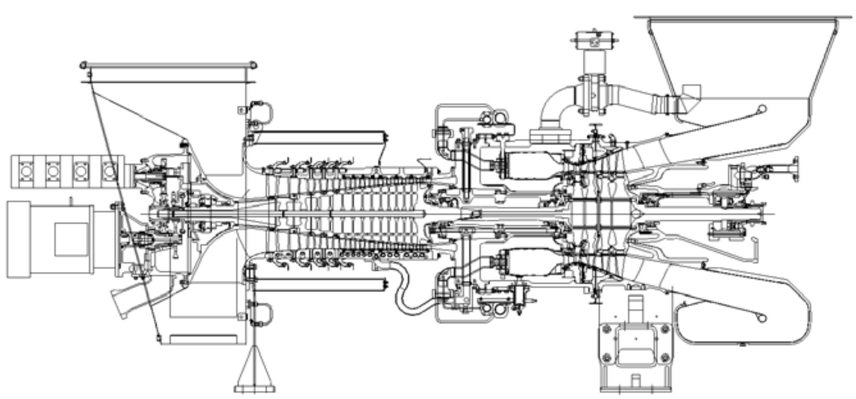


**Figure 3. Current Production Taurus 70 (Annular Combustor)**

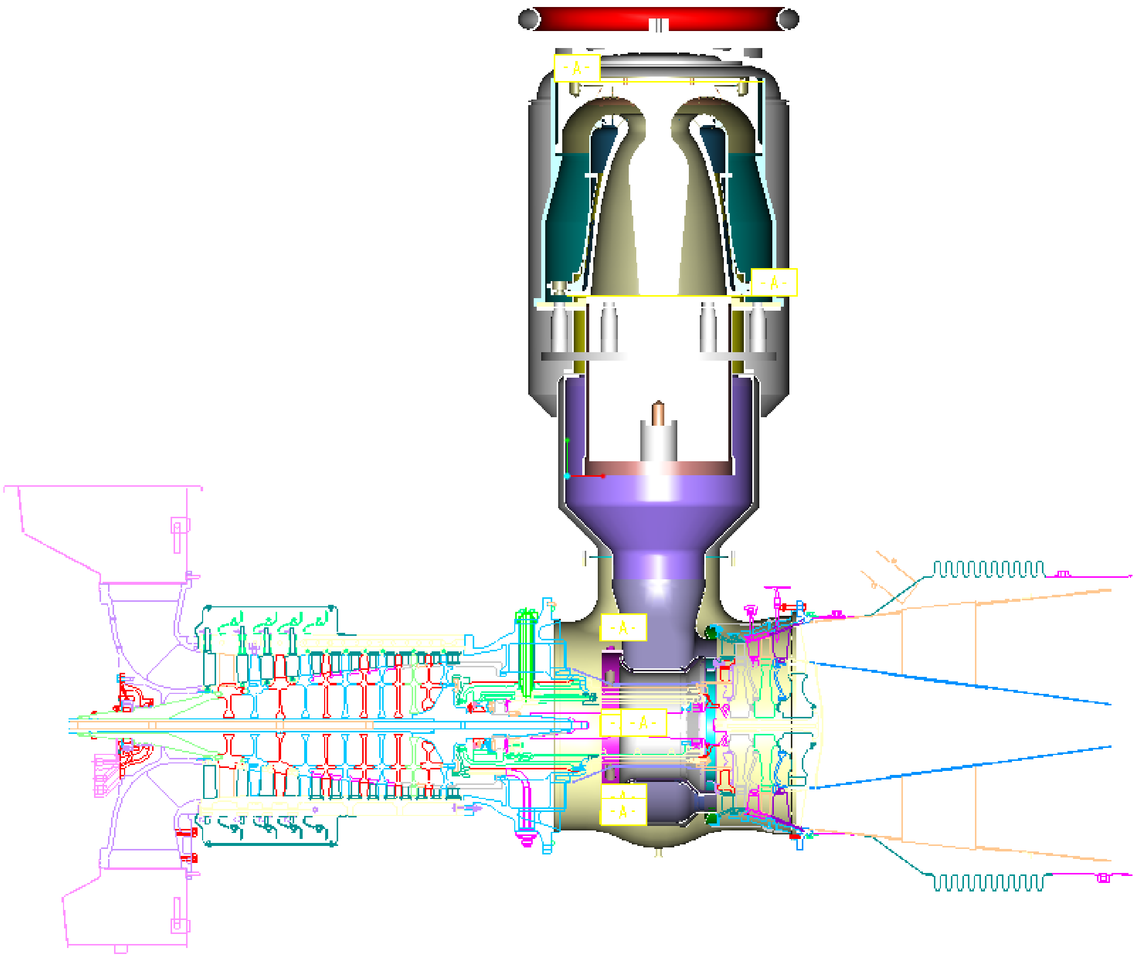


**Figure 4. Cross-Section of Catalytic Combustor-Fired Gas Turbine Concept**

Although the production T-70 engine profile is impacted significantly by the catalytic combustor, the impact on the T-70 package envelope is qualitatively less severe. Figure 5 presents a conceptual layout of a catalytic T-70 installed in an enclosure. The primary change to the enclosure is the addition of a "top hat" section that allows the catalytic combustor to fit within that structure.

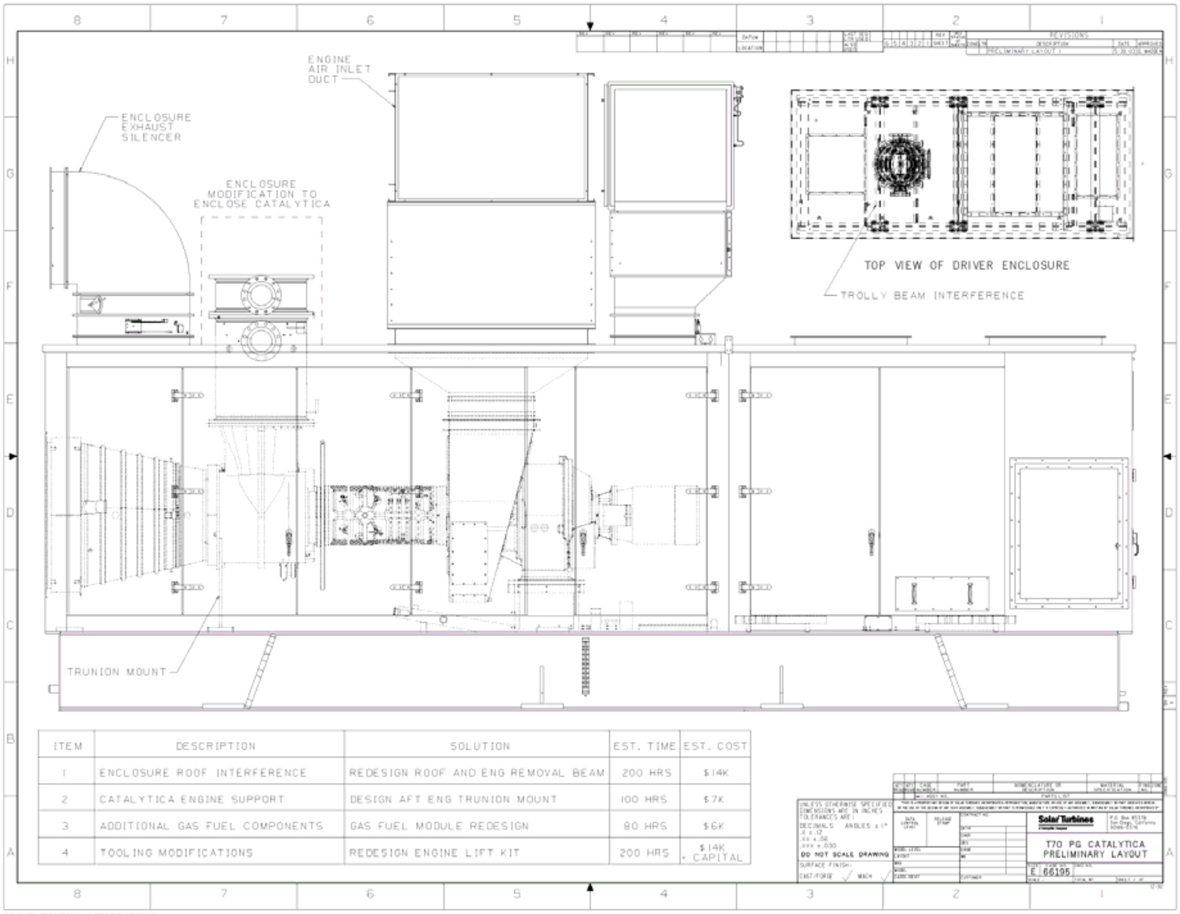



**Figure 5. Catalytic Combustor-Fired Taurus 70 Package Concept**

It should be noted that Figure 5 is a conceptual drawing and does not reflect full consideration of the changes required to adapt the enclosure for the catalytic engine. This effort did not address the structural additions that would be required to the package to support the combustor. Similarly no consideration was given to installation/removal of the engine in the field. These details were deemed beyond the scope of the project although they would be important considerations in developing a practical system for the gas turbine market.

One component of the catalytic T-70 engine that was identified as a significant development challenge was the high temperature scroll. The scroll is a large part (typically sheet metal) situated between the BOZ and the turbine inlet section of the engine. It carries the hot combustion products from the BOZ to the turbine inlet. The scroll is geometrically complex as it transitions from the circular cross-section of the combustor exit to the annular geometry of the turbine nozzle inlet (Figure 6). No comparable piece exists in the production T-70.

The scroll interior is subjected to the highest temperatures of the gas turbine cycle, combustor exit temperature. As such, cooling of the exterior of the scroll is critical in achieving acceptable service life from this complex, expensive part. Cooling is a challenge because of the complex geometry of the scroll, the large surface area that must be cooled, and the limited amount of air that is available for cooling.  For lean combustion systems such as the catalytic combustor, so much of the engine airflow is used to feed the combustion process that little remains for cooling of the engine hot section.

To assess the feasibility of developing a durable scroll for the catalytic T-70 system, a design study of the scroll was initiated with and largely performed by Belcan Corporation.  The objective of the study was three-fold:

- Develop a conceptual design of the scroll
- Fabricate a sub-scale model of the scroll and through flow visualization characterize the complex flow field on the outside the scroll.  This experimental effort was used to identify sections of the scroll that would be the most difficult to cool.
- Conduct heat transfer analyses to validate that the cooling air available was adequate to cool the scroll

In effect, the scroll study represented a tollgate for the combustion system development. Without positive results from the scroll assessment, the feasibility of developing a practical and cost-effective catalytic combustion system would be low.

The results of the scroll assessment are presented in Appendix I-B.  The major conclusion of the study was that scroll cooling appeared to be feasible with the available air, but the development would have to address the difficult challenge of cooling the aft side of the scroll.  This area does not experience direct impingement by the compressor discharge air so enhanced cooling techniques (finned surfaces) will be necessary.

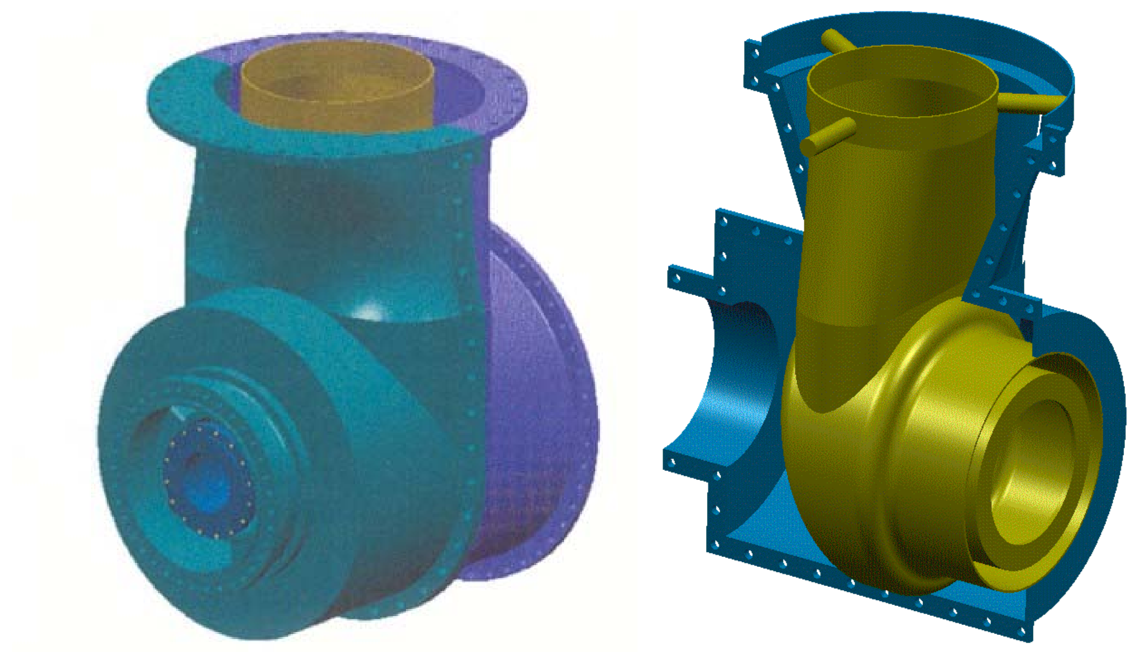


**Figure 6.  Catalytic Combustion System Scroll Concept**

## 3.2. Catalytic Combustion System Fabrication (Task 2.2)

With the completion of the combustion system design and scroll feasibility study, the combustor hardware was fabricated for testing. The hardware is shown in Figures 7 to 11.

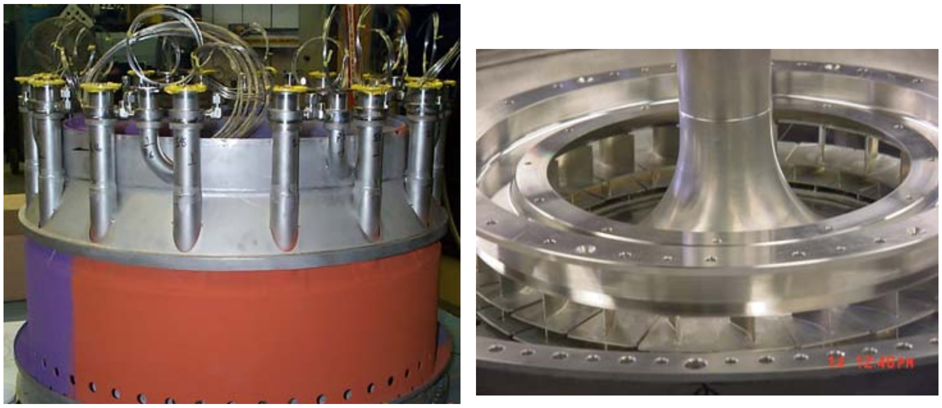


**Figure 7. Preburner/Premixer**

**Figure 8. Reactor Module**

**Figure 9. BOZ**

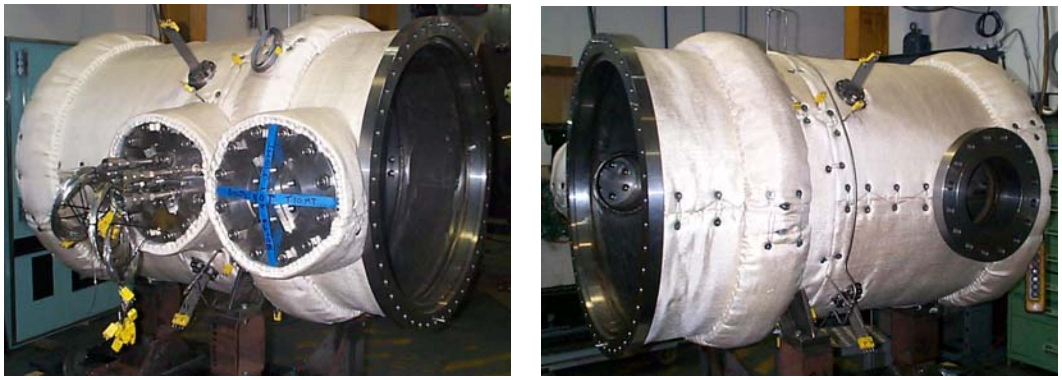


**Figure 10.  Combustor Assembly**

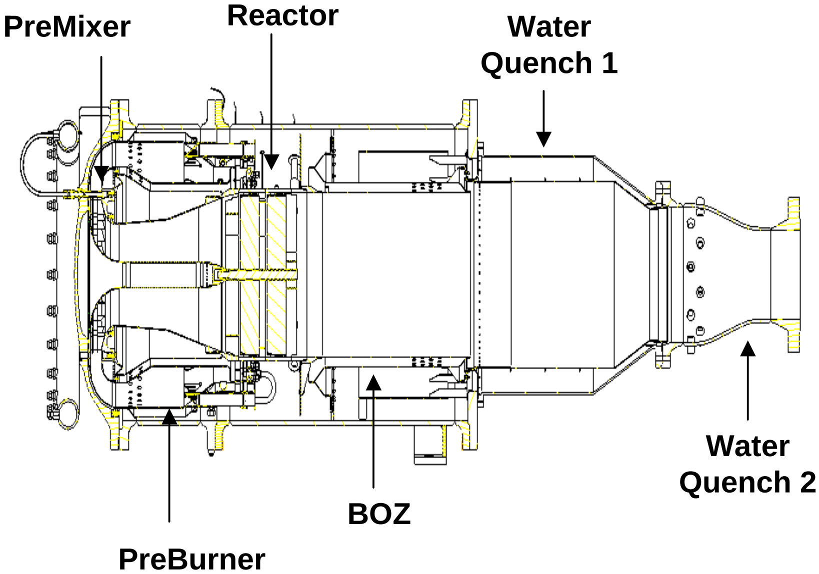



**Figure 11.  Combustor Test Rig**

## 3.3. Component Rig Test (Task 2.3)

A number of combustion system component tests were conducted prior to assembly and evaluation the system as a whole at T-70 conditions.

### *3.3.1. Component Flow Testing (Subtask 2.3.2)*

Atmospheric pressure tests were conducted to document component pressure drops, fuel/air premixing effectiveness, and the premixer exit/reactor inlet velocity profile. Performance was found to be inline with design targets. Details of these tests are presented in Appendix I-C.

### *3.3.2. Atmospheric Pressure Testing (Subtask 2.3.4)*

An atmospheric pressure test of the entire system was conducted to verify preburner and reactor light-off, measure preburner $NO_x$ emissions and document component temperatures. Summaries of key test findings are provided below with full details presented in Appendix I-D.

#### *Light-Off Tests*

Preburner light-off was verified over a range of inlet air temperatures and flows. The preburner showed good light-off characteristics down to a primary zone equivalence ratio of 0.4.

#### *Preburner Primary Stage Operating Range*

The premixer was shown to be operational over a simulated engine load range of 0 – 100% for a wide range of ambient temperatures. This easily meets the preburner design requirements.

#### *Preburner Wall Temperatures*

The outer and inner liners of the preburner were instrumented with thermocouples to monitor wall temperatures. For inlet air temperatures of 700° to 900 $^0$F, the outer liner wall temperatures were below 1375 $^0$F, well within the design target of 1700 $^0$F.

The inner liner wall temperatures showed a maximum of 1400 $^0$F over a range of conditions corresponding to 50-100% engine load. Below 50% load, peak inner wall temperatures approached 1700 $^0$F at locations directly opposite from the secondary jets. As the preburner will see minimal operating time at low loads, the current liner temperatures were deemed satisfactory for rig testing.

#### *Preburner Emissions*

Preburner $NO_x$ concentration is arguably the critical system performance parameter as it essentially determines the gas turbine $NO_x$ emissions. Prior testing has demonstrated that virtually no additional $NO_x$ is produced in the catalytic reactor.

$NO_x$ measurements were conducted over a range of preburner inlet air temperatures and flows. Typical $NO_x$ data are presented in Figure 12 as a function of premixer flame temperature. The data have been adjusted to reflect engine emissions (rather than premixer emissions) by accounting for the dilution effect of the turbine and scroll cooling air injected downstream of the catalytic reactor. With the premixer operating below about 2400F, $NO_x$ emissions are seen to be below 1 ppm. These results were viewed as excellent since experience with other well-mixed, lean combustion systems suggested that there would be little increase in $NO_x$ at elevated pressures.

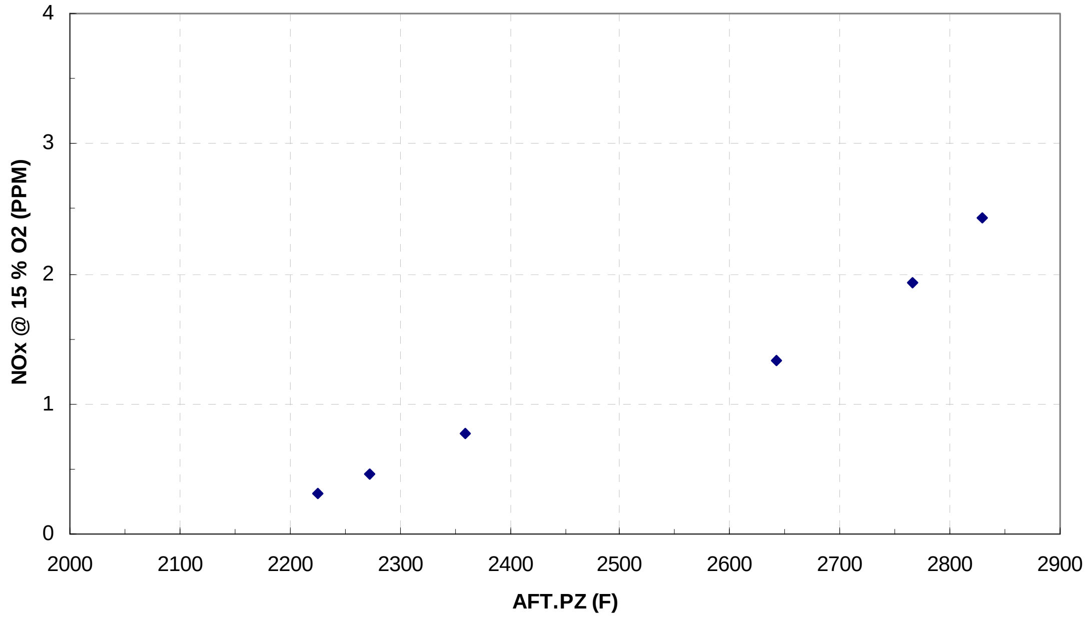



**Figure 12. Preburner $NO_x$ as Turbine Exhaust Emissions**

### *Other Preburner Performance Characteristics*

Additional assessments of the premixer at atmospheric conditions showed the following:

- Preburner exit temperature profile was extremely flat
- Pressure drop met the design goal.
- Mixing effectiveness was adequate to meet the fuel-air uniformity specification

Based on these tests, the preburner/ premixer performance was deemed excellent and acceptable for high pressure testing.

### *3.3.3. High Pressure, Subscale Catalyst Testing (Subtask 2.3.5)*

Catalyst tests were conducted by CESI to validate that their catalyst and wash-coat materials were suitable for the T-70 operating conditions. High pressure testing was conducted using subscale catalytic reactor modules. The tests evaluated emissions ($NO_x$, CO, UHC) on natural gas, pressure drop, and gas and metal temperatures. The test results confirmed the appropriateness of the full-scale module design for the T-70. More detail is provided in Appendix I-E.

## 3.4. Loop Engine/Full Scale Rig Test (Task 2.4)

Two facilities were available for testing of the full-scale catalytic combustor. Solar Turbines' "loop" facility is configured to allow combustor testing in conjunction with an early model Centaur engine. The loop allows transient performance to be assessed but it is limited in air flow and maximum operating pressure (approximately 105 psia).

Alternatively, Caterpillar maintains a higher pressure (150 psia) rig test facility at the Cat Tech Center (CTC). The CTC facility allows testing over a larger range of operating conditions than the loop although transient operation cannot be assessed. Because of the greater flexibility in testing, the decision was made to conduct combustor testing at CTC. Tests at CTC were run with air flow scaled to the reduced operating pressure. This maintained combustor gas velocities at engine design levels.

Testing at CTC was conducted in two phases. Initial testing focused on the performance of the preburner and the premixer. The catalytic reactor was in place but was not fueled. Subsequently, the entire combustion system was tested. A test summary is presented below with a more complete report provided in Appendix I-F.

The catalytic combustor performed extremely well during the CTC rig tests. Virtually all of the performance goals were satisfied. The tests indicated that $NO_x$ emissions could be controlled below 2.5 ppm over a simulated load range of 50 to 100%. Test data showed a design point $NO_x$ concentration of 1.7 ppm (15 % $O_2$), which is consistent with the assumption that $NO_x$ is formed primarily in the preburner. The overall system pressure drop was less than 3.5 %, thus meeting the design requirement.

Testing was at a lower pressure than the T-70 full load pressure (150 psia vs. 250 psia), however, component testing indicates no strong impact of pressure on $NO_x$. The CTC tests provide a high level of confidence that full pressure testing will show similar $NO_x$ levels.

The emissions data obtained at CTC may actually be slightly higher than data obtained at actual T-70 conditions. At CTC it was necessary to over-fire the preburner to reach the target reactor inlet temperature (actual temperature rise of 440 $^0$F vs.186 $^0$F design point rise). At the design preburner temperature rise, $NO_x$ levels will be lower.

Of particular importance, the CTC tests demonstrated the excellent performance of the preburner and premixer. Specifically, the wide turndown of the preburner is advantageous in extending the useful life of the catalytic reactor. As catalyst effectiveness decreases slowly with time, reactor performance can be recovered by increasing the preburner exhaust temperature. If the preburner can be fired at increasingly higher temperatures without exceeding $NO_x$ limits, the catalytic reactor will continue to function as required. The low $NO_x$ capabilities of the preburner suggest that the reactor should exhibit a functional life similar to levels seen by CESI in their Kawasaki system (~ 8000 hours).

## 3.5. Lean Catalytic Combustion System Assessment

In support of the technology down select process, the CESI combustion technology was assessed in eight areas relating to performance, development risk and commercial viability. Table 2 presents the assessment results and corresponding comments. The assessments were done on a qualitative basis and a comparative assessment of the Alzeta nanoSTAR™ technology is presented in Table 3.

**Table 2. Assessment of Catalytic Combustion System Commercialization Risk Factors**

(Green = Low, Yellow = Medium, Red = High)

| RISK FACTOR | RISK LEVEL | COMMENTS |
|---|---|---|
| SUB-2.5 PPM NOX CAPABILITY | G | Emissions demonstrated in full-scale rig test |
| PROJECTED PRODUCT COST | R | High due to premixer/preburner complexity, scroll cost and reactor cost. Projected as higher than SCR. |
| EASE OF INTEGRATION | R | Difficult integration of can combustion system into engine designed for annular geometry |
| DEVELOPMENT RISK | R | Significant risk associated with scroll cooling and thermal stresses |
| DUAL FUEL CAPABILITY | R | Liquid fuel capability not demonstrated. Propane backup a possible but unproven option. |
| DEMONSTRATED DURABILITY | G | Catalyst durability demonstrated in Kawasaki field test. |
| IMPACT ON PACKAGE COMPLEXITY | Y | Moderate level of modification needed to package. |
| RETROFIT POTENTIAL | R | Significant effort to retrofit. Low market potential. |

**Table 3. Comparison of Combustion System Risks: LC vs. nanoSTAR™**

(Green = Positive/Low Risk, Yellow = Neutral/Medium Risk, Red = Negative/High Risk)

| | LEAN CATALYTIC | SURFACE COMBUSTION |
|---|---|---|
| SUB-2.5 PPM NOX CAPABILITY | G | Y |
| PROJECTED PRODUCT COST | R | G |
| EASE OF INTEGRATION | R | G |
| DEVELOPMENT RISK | R | Y |
| DUAL FUEL CAPABILITY | R | R |
| DEMONSTRATED DURABILITY | G | R |
| IMPACT ON PACKAGE COMPLEXITY | Y | G |
| RETROFIT POTENTIAL | R | Y |

### *3.5.1. $NO_X$ Emissions Capabilities*

Rig testing has shown that the catalytic combustion technology is capable of limiting $NO_x$ formation to levels near 1 ppm in a rig environment. Although the quantity of emissions data is limited, it reflects positively on the capability of CESI's system to meet a < 3 ppm $NO_x$ guarantee. It should be realized, however, that duplicating rig test performance on an engine may entail significant risk due to site conditions and the individual performance characteristics of the engine. Duplicating performance repeatedly on a production basis adds more risk.

Beyond meeting the target $NO_x$ level, a practical combustion system also must demonstrate a reasonable operating range over which low emissions can be sustained. Prior experience suggests that a 100F turndown in primary zone operating temperature (from the design point) is the minimum acceptable range to achieve the operational stability required in a gas turbine. Rig testing has shown that the catalytic combustion technology is capable of meeting this operating guideline.

Rig testing preluded any assessment of the transient performance of the combustion system. While $NO_x$ emissions during transients are not typically an issue, combustor stability and performance must be adequate to allow the combustor to operate from light-off to full load without combustor flameout or damage to the engine. Demonstration of this capability requires engine testing outside the scope of the current project.

### 3.5.2. Durability

Of the many aspects of gas turbine performance, durability is one of the most difficult to demonstrate early in the product development process. The difficulty lies in the inability to duplicate engine operating conditions in a test rig. Traditionally, durability is demonstrated through a field test of one or more preproduction engines with the goal of accumulating a minimum of 8000 operating hours. In commercial service, industrial gas turbine users expect 30,000 hours of combustor life before an overhaul.

Through field tests on smaller turbines, CESI has demonstrated that the catalytic reactor is capable of providing at least 8000 hours of operation before a reactor replacement is required. This time period is about the shortest that most turbine operators would accept if the changeout could be coordinated with an annual inspection. The need for an annual replacement of the CESI reactor is a significant cost adder to the technology. Efforts to extend the reactor life should be a prime focus in any future development work.

It should be noted that catalytic reactor service life is determined not only by catalyst activity (or "life") but also preburner performance. A preburner that generates very low $NO_x$ levels will extend reactor life since more catalyst degradation can be tolerated before $NO_x$ emissions rise unacceptably. Conversely, a preburner with higher $NO_x$ emissions will require more frequent reactor replacement as even a small degradation in catalyst activity may result in excessive $NO_x$.

### 3.5.3. Combustion System Integration

Of the combustion systems evaluated, the CESI combustion system requires the greatest level of engine modification. The catalytic system employs a single cylindrical reactor module that does not package easily as a replacement for the T-70 annular combustor. A major engine redesign will be needed to convert the T-70 (or any engine with an annular combustor) to a system accommodating a single can. The nature of the changes has been discussed previously. Changes include accommodation for a larger, more complex combustion system, addition of a scroll in the engine flow path, and major changes to the engine pressure casings. Not addressed but also important is the external structure required to support the combustor.

### 3.5.4. Manufacturing Status

During the program Solar Turbines manufacturing staff and a manufacturing consultant to Solar Turbines conducted an inspection of CESI's manufacturing facility in Arizona. The conclusion of the inspection team was that CESI was well capable of providing reactor modules for a commercial catalytic combustor-fired gas turbine product. CESI was already in production to support the 1.5 MW Kawasaki engine. At that time there were approximately five units in operation. The CESI facilities were seen as adequate to support expanded production for the T-70.

### 3.5.5. Projected Cost

Projections of the relative costs of the candidate combustion technologies were made to support the down select process. It should be noted that the cost projections were very preliminary. Costs were estimated based on the prototype component designs that existed at that time. In addition, order-of-magnitude estimates were used to define the cost associated with the engine design modifications. Finally, the projections were based on pricing provided by Solar Turbines' project partners. CESI had established detailed catalytic reactor pricing based on their earlier manufacturing experience. Pricing for the PCI and Alzeta components was more budgetary.

Table 4 presents the relative costs of the three combustion systems under study. The estimates have been normalized using the CESI system as the baseline. The lean catalytic system is the most expensive of the three.

**Table 4. Relative ULN Combustion System First Cost Comparison**

| | |
|---|---|
| **Surface Combustion** | **0.4** |
| **Rich/Lean Catalytic** | **0.7** |
| **Lean Catalytic** | **1** |

### *3.5.6. Down Select*

Upon a critical evaluation of the areas discussed above, further work on the CESI combustion technology stopped due to its higher engine integration risks and costs (see Table 3 and Table 4). Work to develop and assess the Alzeta combustion system continued in Phase II of this program in parallel with DOE-funded work to further evaluate the PCI combustion system.

# 4.0 Phase II Surface Combustion (Alzeta)

Phase II focused on the engine evaluation of the Alzeta nanoSTAR™ surface combustion technology. An axial combustor configuration, using existing burners and fuel-air premixers, was chosen to undergo evaluation in an existing T-70 engine. The configuration traded the ability to remove injectors in the field for a more near-term test of burner durability, engine control feasibility, and emissions performance.

The effort followed a full-scale rig test at CTC under a prior Energy Commission project. As part of the work in this project, the first test of the nanoSTAR™ system on a T-70 engine was completed. In addition, the T-70 engine test was followed by a series of evaluations on a unique C-40 recuperated engine that enabled the study of the role of combustor inlet air flow distribution and premixer performance on engine emissions.

## 4.1. NanoSTAR™ Combustion System Design

### 4.1.1. Technology Background

NanoSTAR™ is the product name for Alzeta Corporation's ultra-low-emissions gas turbine combustion system. The key feature of the technology is a porous burner surface constructed from sintered metal fibers. A lean premix of fuel (natural gas) and air is passed through this mat and combustion is sustained just above the surface. The burner surface is selectively perforated to create an alternating pattern of high-flow and low-flow zones. This velocity gradient enhances flame stability and enables greater volumetric firing rates without flame liftoff. Coupled with thorough premixing, surface stabilization allows combustion to take place at very low flame temperatures (below 2800°F). In turn, this low flame temperature produces ultra-low emissions of $NO_x$ (less than 3 ppm corrected to 15% $O_2$) without creating excessive emissions of CO or HC (less than 10 ppm corrected to 15% $O_2$). A typical laminar blue flame pattern of a nanoSTAR™ injector can be seen in Figure 13.

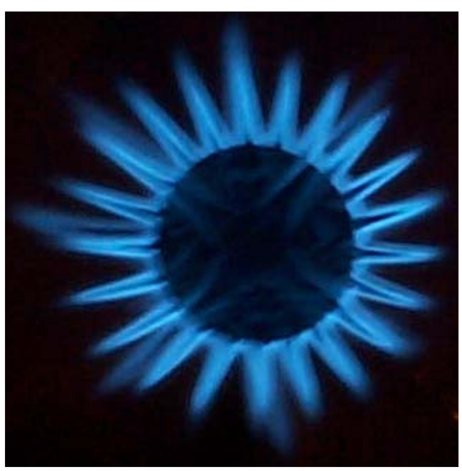


**Figure 13. End View of nanoSTAR™ Injector Displaying Laminar Flame Pattern**

### 4.1.2. System Description

The nanoSTAR™ ultra-low-emissions combustion system for the Taurus 70 engine consists of the following critical components:

- Surface-stabilized main burner
- Internal flow distributor
- Fuel-air premixer
- Diffusion flame pilot burner module
- Backside-cooled combustor liner

The first three components are generally pre-assembled as a single unit and are commonly referred to as the nanoSTAR™ injector. A typical injector assembly is shown in Figure 14. The surface-stabilized burner is the signature component of nanoSTAR™ technology. This selectively perforated porous cylinder resides inside the primary combustion zone. Combustion is stabilized just above the burner surface in the manner described above. Behind the burner surface lies the internal flow distributor. This perforated metal cylinder has been developed specifically to provide uniform flow to all parts of the burner surface, thus preventing localized overheating.

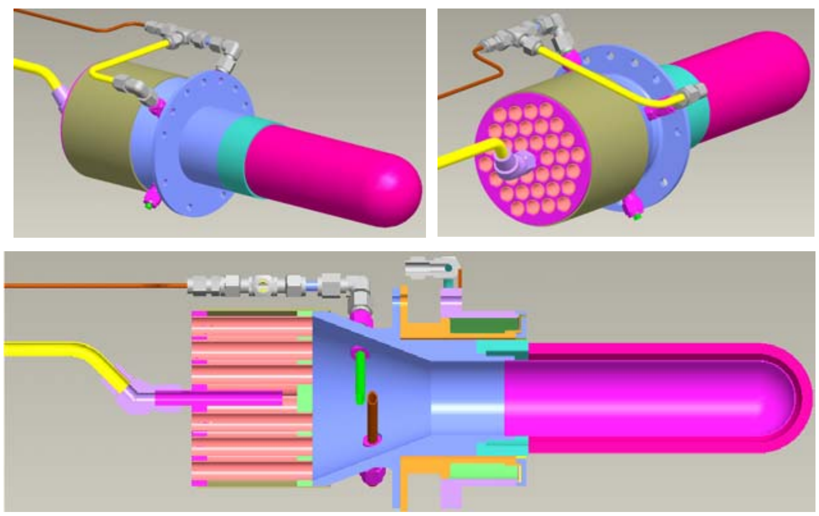


**Figure 14. NanoSTAR™ Injector Assembly**

The fuel-air premixer is an essential part of nanoSTAR™ technology. Spatial fuel concentration uniformity of +/- 3% is generally required at the burner surface in order to achieve optimal emissions. The premixer was the subject of an extensive development effort and several potential designs were evolved. The best candidate design for an engine test was the so-called "multi-tube" premixer. This premixer consists of 36 individual small-diameter tubes that each mix fuel and air on a small scale before combining flow in a converging section upstream of the distributor. The multi-tube premixer design provided an adequate level of mixing and an acceptably low pressure loss in a relatively compact configuration.

Each nanoSTAR™ injector is paired with a diffusion flame pilot module. Pilot fuel is injected downstream through a series of holes surrounding each main burner. The fuel reacts with air from the burner and creates an extremely stable diffusion flame that is used during startup and acceleration to low-emissions mode. Finally, the system is tied together by a backside-cooled annular combustor liner. The nanoSTAR™ combustor liner was specifically designed to prevent any intrusion of cold air into the primary combustion zone, which has been shown to adversely impact nanoSTAR™ emissions. Internal combustor volume was increased to help offset the space occupied by the injectors and ensure complete CO burnout. The injectors and pilot modules mount directly to the upstream dome of the combustor liner, creating the complete nanoSTAR™ system assembly.

### 4.1.3. Combustor Configuration

While the multi-tube version of the nanoSTAR™ injector performed well in single-injector testing, some issues were encountered with placing it inside existing engine hardware. Geometric constraints limited the amount of length available to aid mixing and also prevented injector installation and removal through existing dedicated ports. For these reasons, a novel "canted" combustor was proposed and designed. By angling the combustor away from the engine centerline, additional space and installation access were realized. Figure 15 shows the canted combustor design.

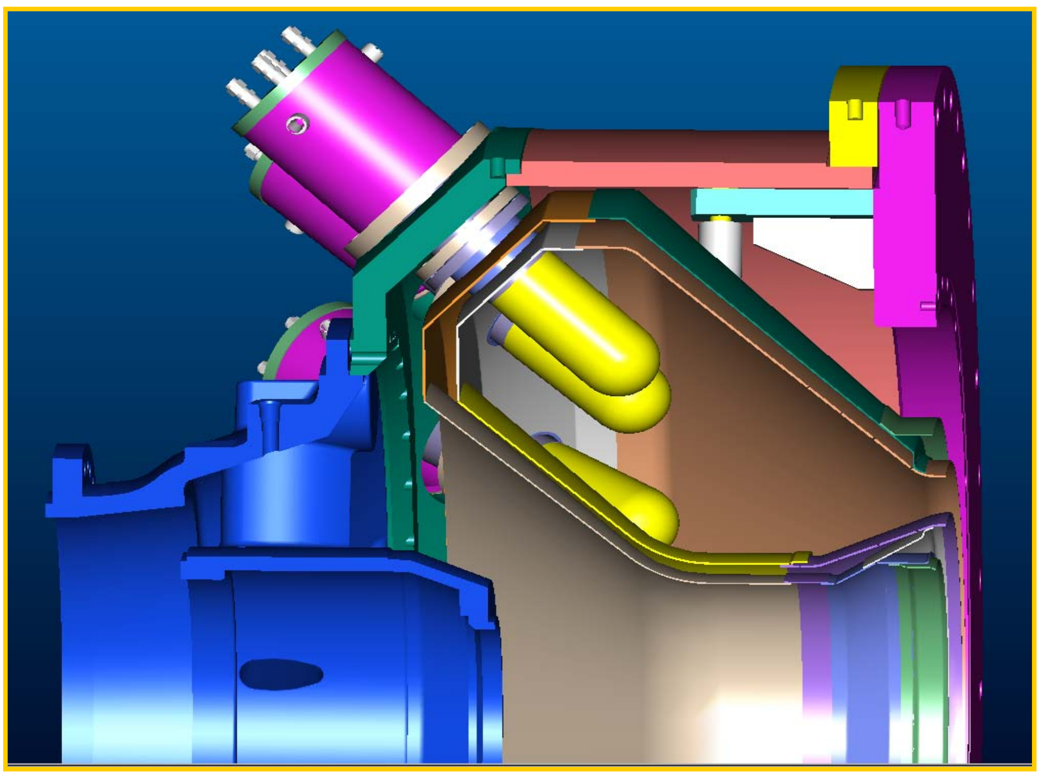


**Figure 15. T-T70 Canted Combustion System**

Unfortunately, implementation of the canted concept would have required a complete redesign of not only the combustor liner, but also the combustor housing and the compressor diffuser. Such extensive modifications to existing engine hardware would require excessive time and cost and thus were found to be outside of the scope of the current effort. Therefore, it was decided to use a more traditional axial combustor configuration for prototype engine testing. Figure 16 shows the axial combustor assembly that was evaluated during engine tests.

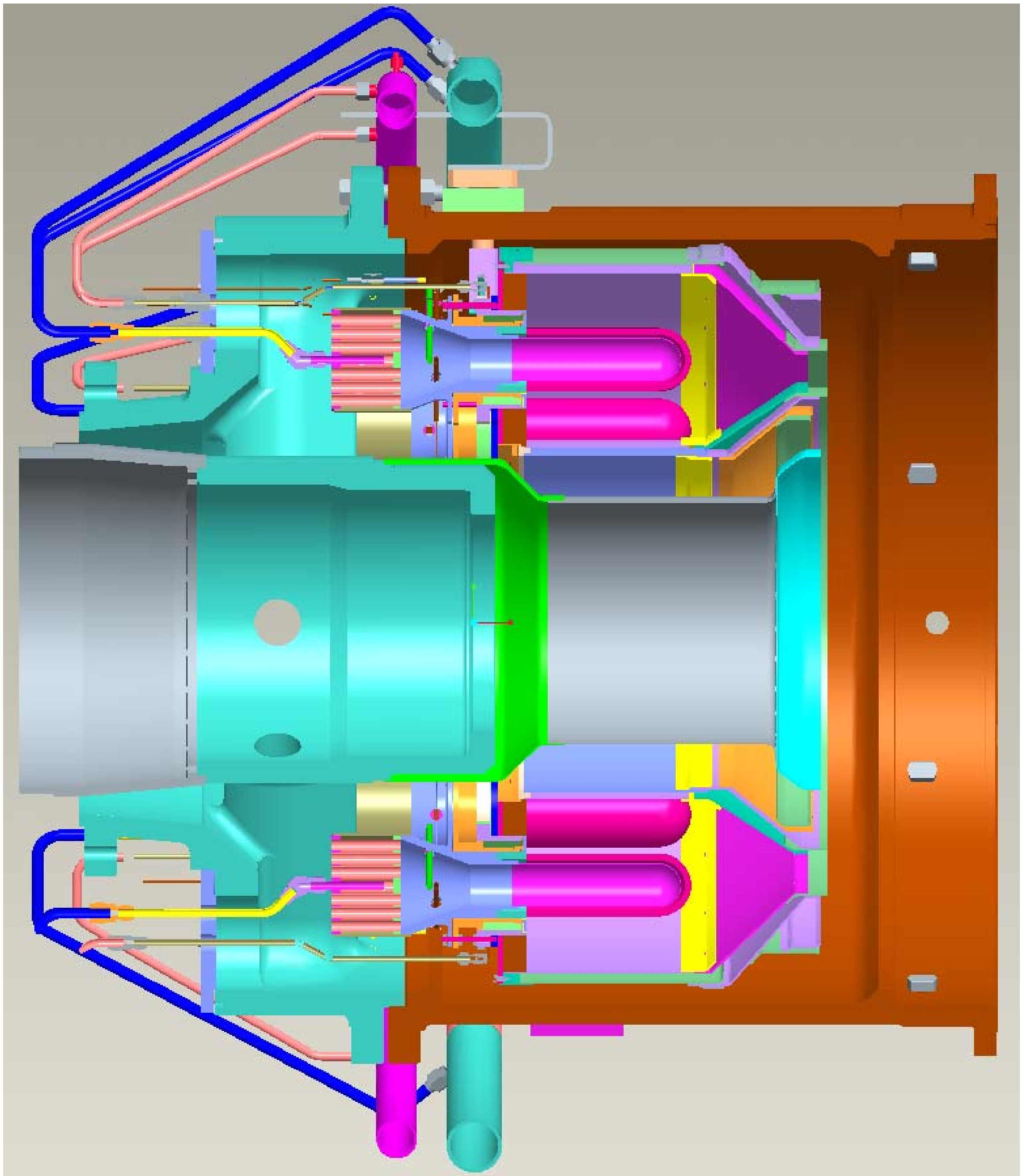


**Figure 16.  T-70 Axial Combustion System**

### 4.1.4. Next-Generation Mixer Design

Installation and removal of nanoSTAR™ injectors in the axial combustor configuration required a major disassembly of the surrounding engine components. Such a procedure would not be practical for routine service of the injectors in the field. The success of the engine tests described below, and the immense development effort associated with the canted combustor concept, has spurred further interest in the axial combustor configuration. The next-generation nanoSTAR™ design would seek to create a more compact premixer that could deliver adequate mixing while enabling retrofit into existing T-70 engines through the axially-configured injector ports. Such a design would facilitate field assessments and enable investigation of long-term system durability. A conceptual drawing of a possible next-generation design is shown in Figure 17.

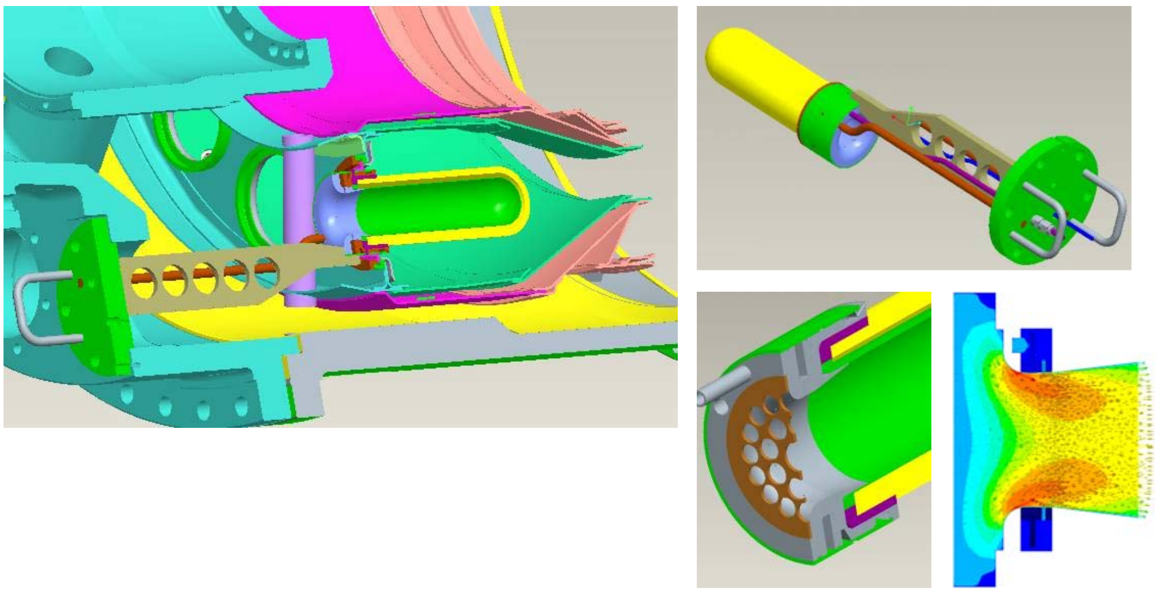


**Figure 17. Next-Generation T-70 Axial Combustion System**

## 4.2. In-House Test (Task 2.5)

Engine evaluations of the nanoSTAR™ combustion system were successfully completed in this project. The most significant results from these activities are summarized below. Full reports for the activities are included in the Appendices.

### *4.2.1. Atmospheric Pressure Testing*

The first step in evaluating the full-scale nanoSTAR™ combustor was a test at atmospheric operating pressure. This test served to qualify the hardware for future engine testing. Functionality, performance and initial durability were investigated and found to be adequate for engine testing.

In accordance with established combustor design practice, initial tests were conducted in Solar Turbines' Full-Scale Atmospheric Test Rig. With no engine hardware downstream of the combustor, the Atmospheric Test Rig provides excellent visual access and a safe platform for initial combustor evaluations. Combustion air temperatures were matched to engine conditions while flow rates were scaled back to atmospheric conditions according to pressure ratio. The following objectives were addressed during atmospheric testing:

- Characterize combustor metal temperatures
- Qualify combustor dome short term durability
- Characterize combustor outlet (gas) temperature profile and pattern factor
- Characterize fuel-air distribution (injector-to-injector)
- Assess reaction uniformity (injector-to-injector)
- Validate system pressure drop and air flow splits
- Characterize emissions and lean stability limits at engine inlet temperatures corresponding to 50%, 75%, and 100% engine load
- Qualify the ignition system and define optimal settings for torch light-off
- Demonstrate system light-around on 100% pilot fuel
- Verify adequate combustor stability on 100% pilot fuel
- Demonstrate transition from pilot to main fuel at elevated inlet temperatures (corresponding to 50% engine load conditions)

In order to achieve these objectives, testing proceeded in five distinct phases. The following table summarizes these phases and details the type of information gathered during each phase.

**Table 5. Summary of Combustion Tests**

| Test | Information Produced |
|---|---|
| Ignition | Reaction Uniformity, Ignition Ease, Light-Around |
| 0% Load | Pilot Flame Stability |
| 50% Load | Combustor Exit Temperature Profile and Pattern Factor, AFR Uniformity, Reaction Structure, Emissions and LBO Limit, Light-Around Transition from Pilot to Main |
| 75% Load | Combustor Exit Temperature Profile and Pattern Factor, AFR Uniformity, Reaction Structure, Emissions and LBO Limit |
| 100% Load | Combustor Metal Temperatures (Thermal Paint Test), Combustor Exit Temperature Profile and Pattern Factor, AFR Uniformity, Reaction Structure, Emissions and LBO Limit |

### *Ignition Test Results*

The control algorithm developed for the nanoSTAR™ T-70 combustion system requires engine ignition with 100% of the fuel flowing through the pilot modules. A single production torch located between two of the nanoSTAR™ injectors is used to ignite the combustor. Combustion is achieved on the two adjacent injectors and quickly propagates around the combustor annulus until all 12 injectors are firing.

This ignition method was successfully demonstrated during atmospheric testing. Torch functionality was robust and light-around of the 12 pilot modules occurred in less than 2 seconds after initial ignition. Upon ignition, an immediate temperature rise of about 400°F was detected in the combustor outlet flow. Combustion was easily sustained after the torch was extinguished and remained stable during acceleration to the simulated 0% load condition.

### *0% Load Test Results*

At simulated 0% load conditions, the stability of the pilot flame was investigated. Normal pilot operation at flame temperatures between 2200° and 2400°F produced a robust and uniform flame structure. Lean extinction assessments demonstrated stability at flame temperatures as low as 1100°F, which would provide excellent operating margin on the engine.

Manufacturing imperfections produced some variation in the amount of fuel admitted through each pilot module. Accordingly, while operating on 100% pilot fuel, some areas of the combustor operated at a higher flame temperature than others. This phenomenon can be observed as variations in flame intensity in Figure 18 below. Though not desirable, this variation was not unexpected and was not large enough to be a concern during initial prototype testing.

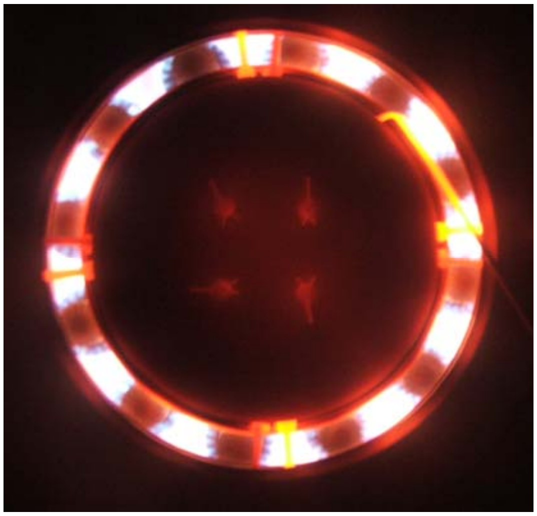


**Figure 18. 100% Pilot Operation at Simulated 0% Load**

### *50% Load Test Results*

Acceleration to a simulated 50% load condition was accomplished with 100% of the fuel still being admitted through the pilots. Reaction structure and stability at the design flame temperature of 2200°F were excellent. Temperatures at the exit plane of the combustor were characterized with the use of thermocouple rakes and found to be within expected limits.

At simulated 50% load, ignition of the main burners was successfully achieved. Fuel flow was quickly transferred from the pilot fuel circuit to the main fuel circuit while the overall flame temperature was adjusted to the design point of 2750°F. This transition to low-emissions operating mode was smooth and robust. At this operating condition, initial tests were conducted to characterize the lean stability and emissions of the nanoSTAR™ system. The results are shown below.

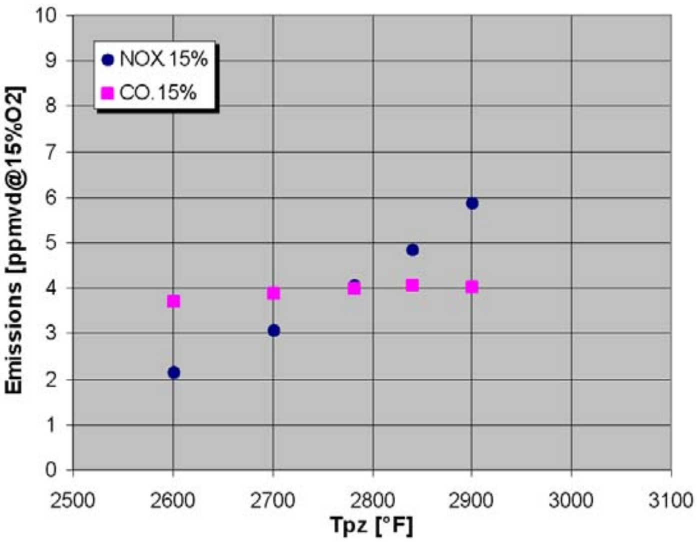



**Figure 19. 100% Main at Simulated 50% Load: Emissions**

Initial evaluations were also conducted to assess the uniformity of the fuel-air mixture among the injectors. A novel sampling method allowed direct measurement of the fuel concentration shortly upstream of the combustion surface of each main burner. These measurements were used to compute operating flame temperatures for each injector. Peak-to-peak flame temperature variation among the 12 injectors was found to be about 119°F, well within the design target of 200°F. This excellent uniformity can be observed in the flame structure shown in Figure 20 below.

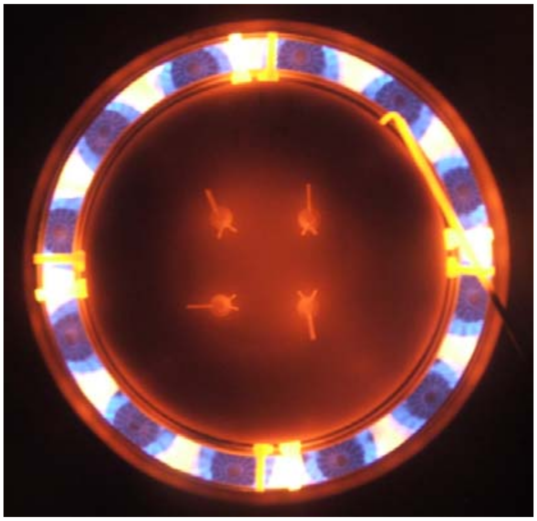


**Figure 20. 100% Main Operation at Simulated 0% Load**

Finally, combustor metal temperatures were monitored and recorded during 50% load testing. A total of 23 thermocouples were installed at various locations on the combustor walls, the combustor inlet dome, and the pilot modules. Peak temperatures recorded during pilot operation (1585°F) and main operation (1165°F) were well within operating limits for Hastelloy X metal.

### *75% Load Test Results*

Acceleration to simulated 75% load conditions was accomplished with 100% main fuel. Combustor performance at this condition was similar to that observed at 50% load. Results of emissions and lean stability tests are shown in Figure 21 below.

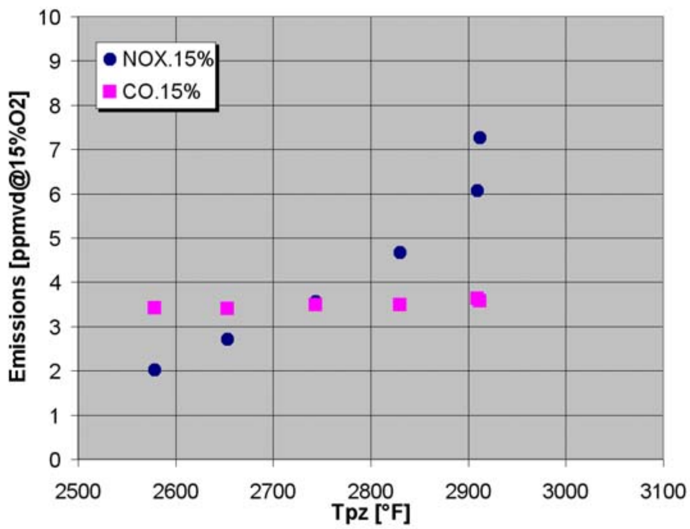



**Figure 21. 100% Main at Simulated 75% Load: Emissions**

### *100% Load Test Results*

Extensive testing of the combustor was performed at simulated full load conditions, which are of the greatest interest for low-emissions operation. Figure 22 below shows emissions and stability results for the nominal full-load operating condition (average burner surface throughput velocity of 15.6 ft/s). To explore performance sensitivity of the combustion system, tests were also conducted at combustor air flow rates higher and lower than the design point. It was found that emissions performance was essentially unaffected by changes in throughput velocity. Uniformly low CO emissions suggested that the internal combustor volume was sufficiently large for the desired engine performance. Emissions results at three different throughput velocities are presented in Figure 23.

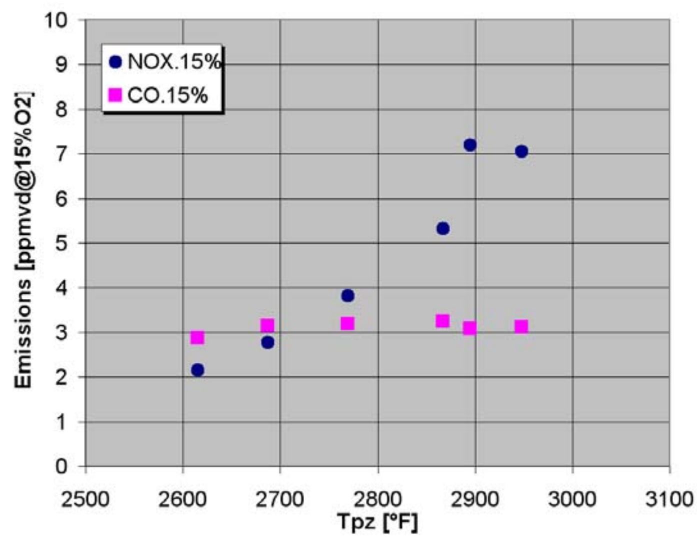



**Figure 22. 100% Main at Simulated 100% Load: Emissions**

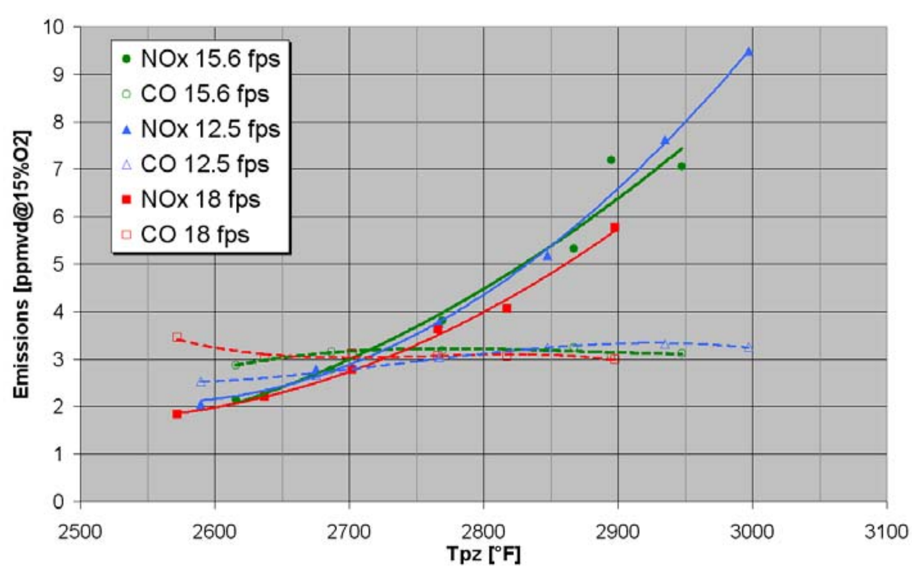



**Figure 23. Impact of Residence Time on Emissions: 100% Load Simulation**

Direct measurement of the fuel-air mixture in each burner was again performed at the simulated full-load condition. Peak-to-peak variation in calculated flame temperature among the 12 injectors was found to be 95°F. Figure 24 shows this excellent reaction uniformity. The locations of the hottest and coldest injectors matched those observed at 50% load, indicating that fuel and air distribution are not sensitive to changes in load.

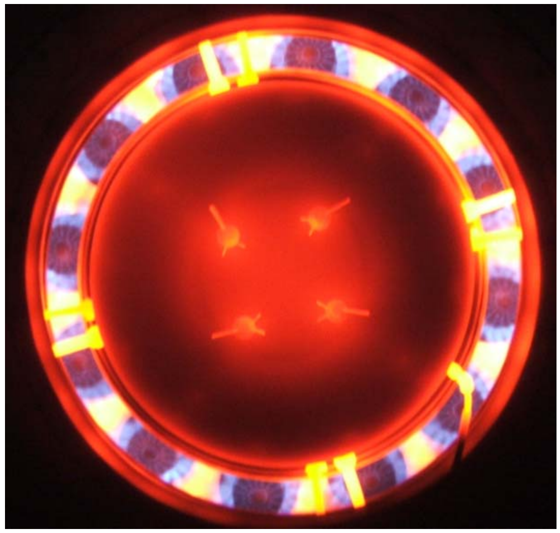


**Figure 24. 100% Main Operation at Simulated 100% Load**

A critical test involved measurement of the combustor outlet temperature profile at full-load conditions. Compliance with T-70 engine specifications was required in order to proceed with in-house engine testing. Initial measurements did not meet the specification. Therefore modifications to the combustor dilution air hole pattern were made and the test was repeated. The modified combustor displayed an exit temperature profile that fell within allowable limits across the entire outlet span, as indicated in Figure 25. The overall combustor pattern factor was measured to be 0.23, which is below the specified limit of 0.25.

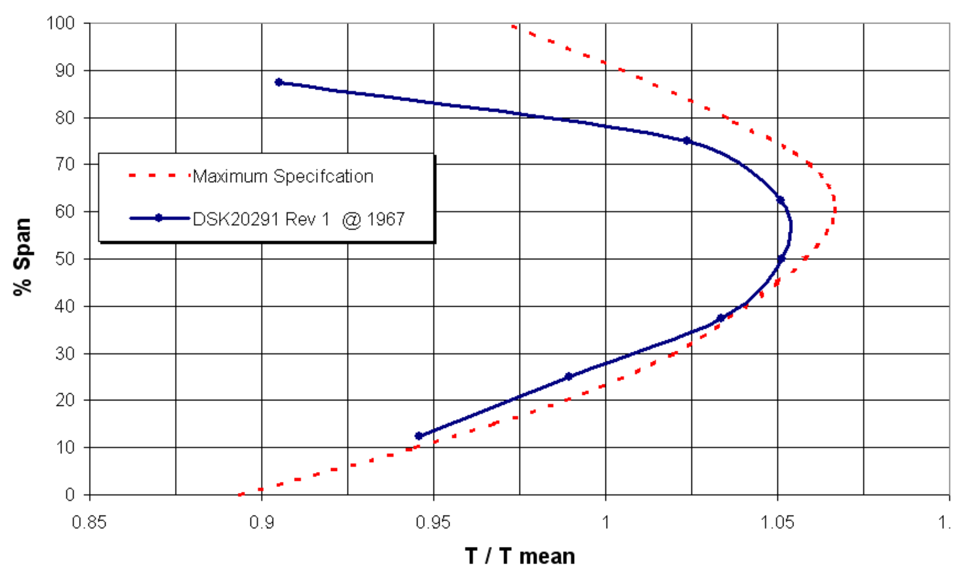



**Figure 25. Combustor Exit Temperature Radial Profile: 100% Load Simulation**

Finally, metal temperatures were once again recorded at the full-load operating condition. Temperatures were higher than those observed at 50% load (100% main operation) due to the higher inlet air temperature. The highest recorded metal temperature at simulated full-load was 1251°F at one particular location on the combustor wall. Since all measured metal temperatures were well below operating limits, a planned thermal paint test was deemed to be unnecessary.

### *Atmospheric Test Summary*

Full-scale atmospheric combustion tests were successfully completed. Tests were conducted to investigate ignition, light-around, flame stability, reaction uniformity, pilot-to-main transition, combustor exit temperature distribution, component metal temperatures, and emissions. All parameters were found to be within design limits and the nanoSTAR™ combustor was qualified to proceed to in-house engine testing.

### 4.2.2. Engine Testing

Following the atmospheric pressure test, the nanoSTAR™ combustion system was tested on a Taurus engine for the first time. Testing was conducted using a natural gas-fired T-70 engine on site at Solar Turbines. Engine startup and acceleration to 50% load were successfully demonstrated. Most performance parameters were met or exceeded, but emissions performance at 50% load fell short of project goals. Acceleration to full load was prevented by a suspected internal air leak. Several diagnostic tests were performed to investigate this leak and the sub-par emissions performance.

The objective of the in-house engine test was to evaluate steady-state emissions, short-term hardware durability, and system stability during transient engine operation. Specifically, the tests sought to demonstrate:

- Smooth and repeatable ignition using the pilot fuel injection system
- Smooth and repeatable transition from 100% pilot operation to main low-emissions mode at 50% load
- Stable operation on the main burners from 50 to 100% load
- Smooth and repeatable transition from main low-emissions mode back to 100% pilot operation
- Ultra-low emissions between 50 and 100 % load (< 5 ppm $NO_x$, < 10 ppm CO @15% $O_2$).

The following combustor performance data were collected:

- Combustor emissions
- Combustor dynamic pressure fluctuations
- Combustor pressure drop
- Combustor and pilot metal temperatures
- Combustor exit temperature
- Fuel concentration inside each injector

#### Start and Acceleration

After some preliminary adjustments to the control logic, the engine start and acceleration cycle was demonstrated to be robust and repeatable. The start cycle began with a standard engine air purge accomplished with an electric starter motor and no combustion. Ignition of the nanoSTAR™ pilot modules occurred at crank speed with the use of a modified T-70 torch igniter located in between two injectors. Ignition rapidly spread to all 12 injectors and then engine accelerated smoothly to idle (72% NGP) using standard T-70 control algorithms. At idle, the algorithm modulated the flow of bleed air in order to maintain the combustor primary zone temperature (TPZ) at the desired set-point. During 100% pilot operation, this set-point was initially fixed at 2200°F. The engine was then successfully accelerated to 83% NGP while fueling only the pilot modules.

Transfer of fuel from the pilot modules to the main burners was accomplished in two phases. The first phase, designated "Ramp A", involved transferring 90% of the total fuel flow from the pilot stage to the main stage. Primary zone temperature was simultaneously increased to 2600°F. Ramp A was executed as a linear ramp with a duration of 30 seconds.

With stable operation on 90% main fuel established, an initial assessment of injector-to-injector premix uniformity was performed. Using a direct sampling method, the average fuel concentration inside each of the 12 main injectors was measured. These concentrations were then used to calculate flame temperatures for each injector. Figure 26 presents these calculations for each injector. The peak-to-peak spread in flame temperatures was about 350°F, which exceeded the design target of 200°F. This spread adversely affected emissions, but was not large enough to pose a significant hardware risk. Throughout testing, a set of 12 thermocouples were used to monitor the power turbine inlet temperature (T5). Despite the unexpectedly high fuel concentration variation among injectors, the T5 distribution conformed to the engine specification.

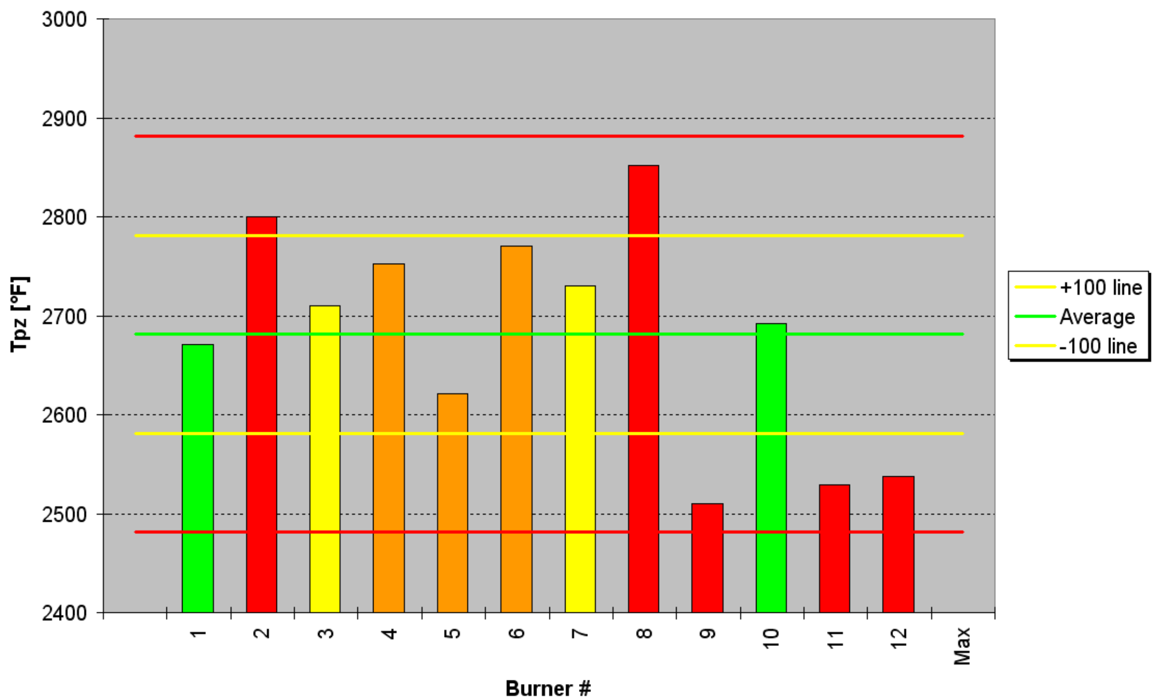



**Figure 26. Injector Premix Survey, 83% Ngp, 90% Main**

After these initial assessments of fuel concentration and combustor exit temperature uniformity were conducted, the remaining 10% of the fuel flow was transferred from the pilot to the main burners. This transition, designated "Ramp B", took place at a constant engine speed of 92% NGP (50% load). The fuel transfer was executed over 5 seconds while primary zone temperature was simultaneously increased to the low-emissions design point of 2750°F. During initial testing, the pilot flames actually extinguished an instant before the design TPZ was reached. Consequently, the engine briefly encountered low-amplitude, low-frequency pressure oscillations known as rumble. These oscillations disappeared as soon as the primary zone temperature reached the desired set-point. The short duration of rumble ensured that no hardware damage occurred. In subsequent tests, the timing of the fuel transfer during "Ramp B" was adjusted in order to avoid engine rumble.

### *Low-Emissions Operation*

With the completion of "Ramp B", the combustor was fully operational in low-emissions mode. A second fuel concentration uniformity assessment was conducted at 92% NGP (50% load). The results of this assessment, shown in Figure 27, were very similar to those previously attained at 83% NGP. Peak-to-peak spread in calculated flame temperature among the injectors was approximately 400°F. Therefore it was concluded that injector-to-injector fuel uniformity was substantially unaffected by engine operating conditions.

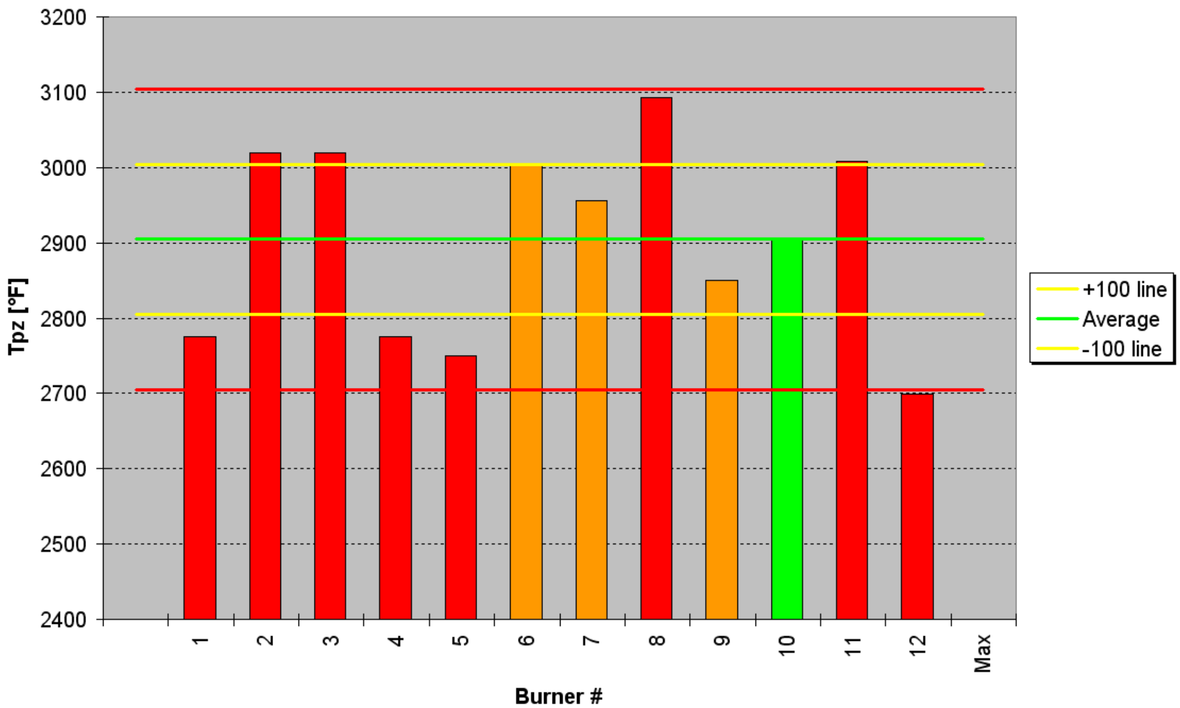



**Figure 27. Injector Premix Survey, 92% Ngp, 100% Main**

Several critical performance parameters were measured while operating in the low-emissions mode. Combustor and pilot metal temperatures were all below design goals, indicating acceptable liner cooling. No significant dynamic pressure oscillations were observed while operating in the low-emissions mode. The combustor exit temperature (T5) profile was once again shown to conform to specifications. In terms of these important parameters, the engine test was deemed a success.

Initial emissions measurements were also performed at 92% NGP. At the design flame temperature of 2750°F, $NO_x$ emissions were approximately 15 ppm (corrected to 15% $O_2$). CO and HC emissions were above the measurable scale of the available emissions analyzers (200 ppm CO and 100 ppm HC).

During operation in low-emissions mode, an apparent internal engine air leak was detected. An unexpectedly low portion of the combustor air was reaching the injectors, which substantially hampered the ability to control flame temperature at higher loads. Acceleration beyond 92% NGP was therefore not possible without potentially overheating the injectors. The engine was shut down in a controlled manner and the initial round of engine tests was concluded.

### *Additional Diagnostics*

After initial testing was completed, it was postulated that the substandard emissions performance could be attributed to the larger-than-expected spread in injector-to-injector fuel concentration. Using a novel in-situ flow test, an attempt was made to quantify variations in the as-installed main fuel circuits among the 12 injectors. A new set of fuel orifices was then designed and installed to compensate for the fuel variations. With these orifices in place, a second test of the engine was conducted. The orifices were somewhat effective as the peak-to-peak variation in flame temperature among injectors was reduced to approximately 250°F. However, the emissions data did not show a significant improvement. $NO_x$ emissions at 50% load were approximately 13 ppm, while CO and HC emissions remained above the scale of the available instruments.

Another suspected factor that could have caused substandard emissions during the engine test was poor premixing within each injector. It was recognized prior to engine testing that the airflow patterns upstream of the combustor would be different in an engine than in the test rigs used for initial burner development. CFD analyses indicated that the jet of air leaving the engine diffuser could create a severely non-uniform flow profile at the inlet of each premixer. The result would be a non-uniform air/fuel mixture within each burner which could lead to poor emissions performance in extreme cases.

Single-injector tests had already confirmed that an airflow bias could have a detrimental impact on emissions and flame structure. Figure 28 shows such a test with an artificially-imposed inlet airflow bias. However, existing data quantifying the flow field on the engine was very limited. Therefore, an attempt was made to quantify the actual flow distribution across the inlet of an injector using a novel in-situ measurement technique on the engine.

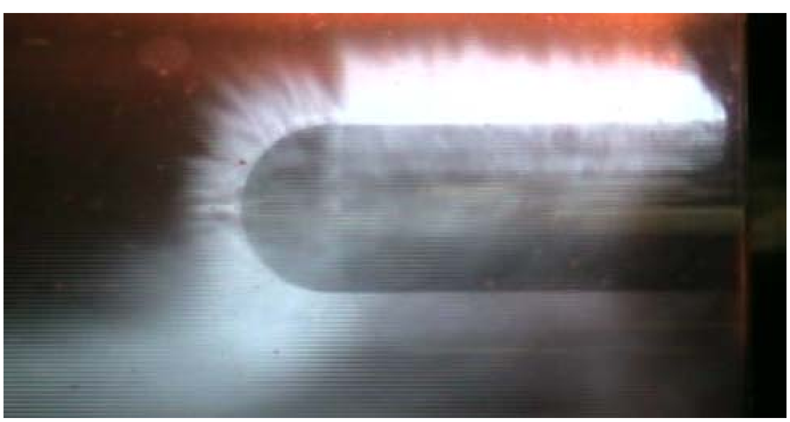
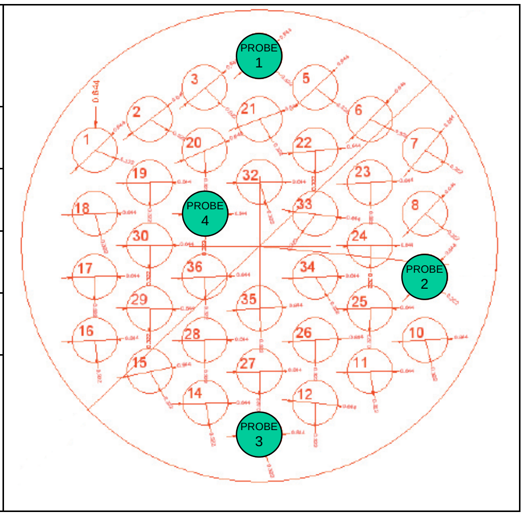


**Figure 28. Simulated Impact of Biased Air Flow on Burner Flame Structure**

One of the installed injectors was instrumented with four individual premix sample probes inserted through four different mixing tubes selected to provide a broad spatial profile. These probes extracted a premix sample from approximately ¼" downstream of the exit of the mixing tube. With the engine running at crank speed, a small amount of fuel was introduced to the instrumented injector and fuel concentration measurements were made for each of the four mixing tubes. Measurements were also made with the downstream "averaging probe" that is used to assess the average fuel concentration in each injector. Table 6 below shows the data collected during this test.

**Table 6. Quantification of Spatial Unmixedness in Injector # 2**

| **Probe** | **Fuel Concentration (Flame T, °F)** |
|---|---|
| 1 | 5.11% (2797) |
| 2 | 3.81% (2338) |
| 3 | 3.20% (2112) |
| 4 | 3.96% (2392) |
| Averaging Probe | 4.26% (2500) |




The fuel concentration measured by probe #1 was 20% above the averaging probe, while probe #3 indicated a concentration 25% below the averaging probe. Extrapolated to full-load design conditions, this non-uniformity would result in a peak-to-peak flame temperature spread of approximately 800°F. Thus the data from this test support the idea that inlet flow non-uniformities are affecting the engine test results. It appears very likely that a significant airflow bias exists within the engine, leading to a significant impact on flame structure of the burner and a detrimental impact on emissions.

A number of assessments were conducted to investigate the suspected air leak that prevented acceleration to full load. The only external air leakages identified by technicians were very minor. Therefore a significant air leakage around the combustor was thought to exist somewhere inside the engine. Any air leak into the primary combustion zone would also have a detrimental impact on emissions. The following potential internal leak paths were identified:

- Through the torch port (into the primary zone)
- Through the injector mounting flanges (into the primary zone)
- Through the combustor dome mounting flange (into the primary zone)
- Through the fishmouth combustor exit interface (into the secondary zone)
- Through the turbine nozzle seals
- Through damaged combustor hardware, if such hidden damage had occurred

After the combustor was removed from the engine, all of these potential leak paths were investigated. Visual inspection of the combustor confirmed that no major hardware damage had occurred during engine testing. All engine components appeared to be properly installed. There were no telltale signs of primary zone leakage such as loose bolts, missing gaskets, or erosion of the combustor dome insulation material. Flow tests of the combustor and first-stage turbine nozzle yielded the expected values. Fishmouth engagement was verified with CMM measurements and by carefully comparing component drawings to the corresponding production parts. While the source of the air leak remains unknown, it is likely that the leak was unique to that particular engine build and was not indicative of a design or manufacturing flaw of the nanoSTAR™ combustor.

#### *Engine Test Summary*

The in-house T-70 engine test represented the first time that a nanoSTAR™ surface-stabilized combustion system was integrated into an industrial gas turbine in a multi-injector annular configuration. Ignition with the pilot modules was smooth and repeatable. Transfer of fuel flow from the pilot stage to the main stage was accomplished using a two-phase control sequence. The engine maintained stable operation at speeds up to 92% NGP (50% load). $NO_x$ emissions were shown to be less than 15 ppm, but CO and HC emissions were high. The engine was successfully shut down after each test run with no detrimental effects observed.

The high $NO_x$ and CO emissions observed were attributed primarily to poor premixer performance. Fuel/air mixing was adversely affected by non-uniform air distribution at the inlet of the injectors. Initial measurements were made to verify and quantify the air flow bias problem. Future tests would seek to address mixture quality by establishing a more uniform airflow field at the inlet of the injectors.

### *4.2.3. Loop Testing*

The initial nanoSTAR™ T-70 engine test was a partial success, but further full-scale evaluations of the combustion system were necessary. Emissions performance on the T-70 engine was significantly worse than expected. In order to improve emissions, an effort was made to improve the uniformity of the air flow field at the inlet of the nanoSTAR™ injectors. This was accomplished by the addition of a perforated "restrictor plate" on the upstream end of each injector, as shown in Figure 29. The additional pressure loss introduced by this plate acts to more evenly distribute air to each of the 36 mixing tubes on the injector.

**Figure 29. Fuel/Air Premixer with "Restrictor" Plate Installed**

To address the flow uniformity issue more quickly and cost-effectively, combustor testing was shifted from the T-70 engine to a more accessible C-40 engine rig. The C-40 test engine was unique in that it had been reconfigured to operate with an external, side-mounted combustor configuration. The engine is commonly referred to as the "loop" engine because of the unique external ducting required. With the exception of the removable restrictor plates, the nanoSTAR™ combustor hardware used in the loop test was identical to that used in the T-70 engine test. Operating conditions were also identical with the exception of pressure ratio, which was 7.5 atm as opposed to 16 atm on the T-70 engine.

Two sets of tests were completed on the loop engine. The first was a baseline test using the unmodified combustor hardware from the prior T-70 test. The second test introduced restrictor plates on each of the injectors. The improved air flow distribution in the second test resulted in $NO_x$ emissions below 3 ppm with less than 10 ppm CO (both corrected @ 15% $O_2$). This represented a significant improvement over the baseline test. Other performance parameters met or exceeded the design goals.

Evaluations on the loop engine involved characterizing performance with and without the fuel/air premixer "restrictor" plates. Upon reaching loop engine full-load, the unique recuperative capability of the facility enabled the combustor inlet temperature to be boosted to T-70 full-load levels. The tests served primarily to characterize emissions and lean stability at maximum engine load. Combustor pressure drop, metal temperatures, dynamic pressure oscillations, reaction uniformity and stability during startup were also investigated.

### *Start and Acceleration*

During testing, the loop engine was started and accelerated a number of times. The control logic consisted of steps similar to those developed for the T-70 engine:

- Ignition on 100% pilot
- Acceleration to 50% load on 100% pilot
- Transition to 90% main at 50% load
- Acceleration to 100% load on 90% main
- Transition to 100% main at 100% load

Smooth light-off, acceleration, and transitions between pilot and main stages enabled successful attainment of maximum engine load. The presence of the restrictor plates did not have any impact on engine operability. Overall, approximately 16 hours of operation and 7 start/shutdown cycles were added to the nanoSTAR™ combustion system. No hardware damage or degradation was evident at the completion of testing.

### *Emissions and Stability at Full Load*

Emissions performance and lean stability were characterized at full load conditions both with and without the presence of the restrictor plates. The loop engine was able to match the inlet air temperature (800°F) and burner throughput velocity (15 ft/s) of T-70 full load at approximately half the operating pressure. Figure 30 shows the emissions data collected at these conditions. The minimum $NO_x$ emissions achieved during the baseline test were about 4.3 ppm (corrected to 15% $O_2$). When the restrictor plates were added, $NO_x$ emissions below 3 ppm (corrected to 15% $O_2$) were observed. CO emissions were also simultaneously lower during restrictor plate testing than during baseline testing. The restrictor plates also appeared to enhance lean stability, extending stable operation below an estimated flame temperature of 2650°F as opposed to around 2775°F in the baseline test.

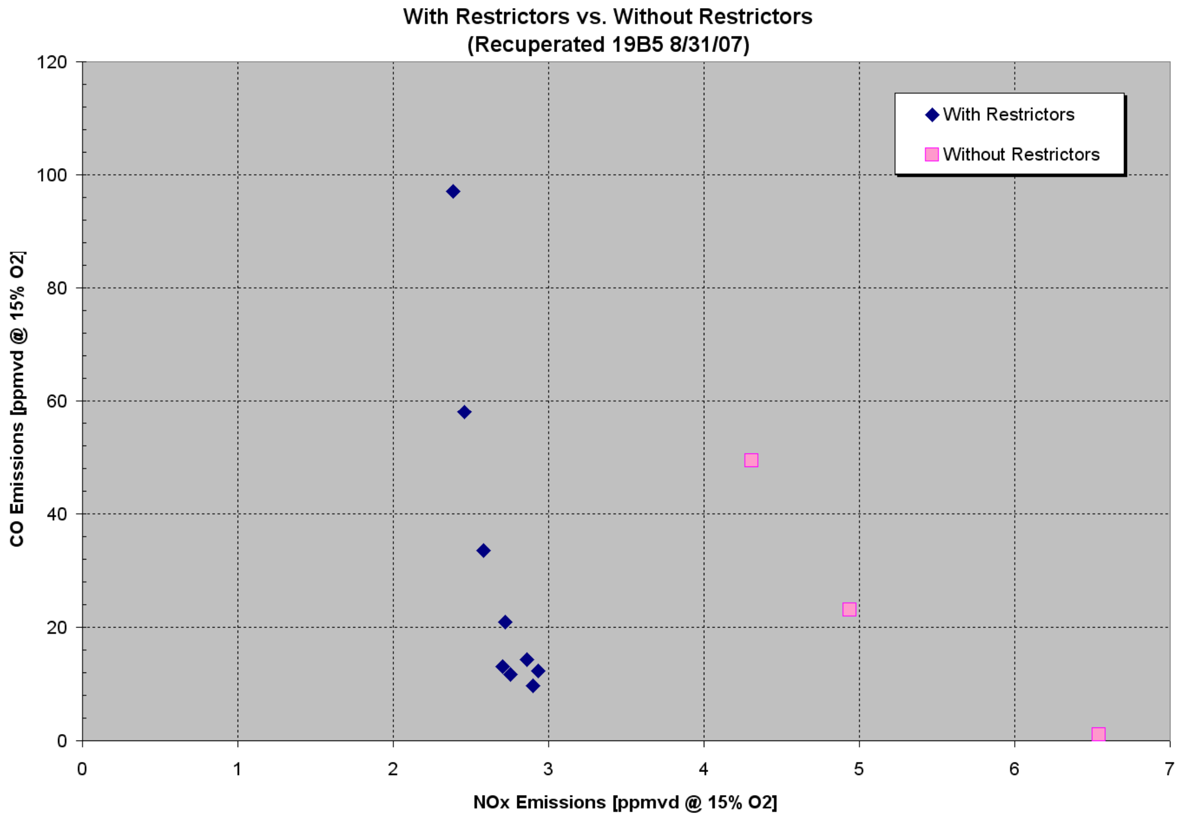



**Figure 30. CO vs. $NO_x$ Emissions: With and Without Restrictor Plates**

In order to further assess combustion stability, dynamic pressure oscillations were monitored using a piezoelectric probe mounted to the combustor torch port. No significant pressure oscillations were detected under any of the conditions tested. The recorded amplitudes were 0.025-0.028 psi (rms) during the baseline test and 0.018-0.021 psi (rms) with the restrictor plates installed. These values are nearly an order-of-magnitude lower than levels typically seen with more conventional low emissions combustion systems.

### *Premix Distribution Assessments*

As in prior testing, each injector was instrumented with a probe capable of sampling a spatially-averaged fuel concentration just downstream of the premixer exit plane. Given concerns about the uniformity of the air flow field upstream of the injectors, additional spatially-resolved fuel concentration measurements were desired during loop testing. In order to acquire these data, four injectors were each fitted with 4-6 additional sample probes inserted through individual mixing tubes. A typical arrangement of these 1/16″ sample tubes can be seen in Figure 29 above. Sample locations were selected in order to provide broad spatial resolution of fuel concentration within the injector.

A complete set of premix concentration data was collected during both baseline and restrictor plate testing. Baseline testing showed that while average fuel concentration varied little from injector to injector, local measurements within an injector varied greatly around its circumference. Variations of up to 25% fuel concentration (the equivalent of nearly 750°F flame temperature) were observed on opposite sides of an injector. Generally the side of the injector closest to the combustor housing received less air flow and therefore operated hotter than the side closest to the engine shaft. These results are consistent with observations made during the T-70 engine test and with predictions made using CFD analysis.

Premix measurements with the restrictor plates installed did not show a significant quantitative improvement in mixture uniformity. Fuel concentration measurements still varied by as much as 25% within an injector. However, the nature of the non-uniformity appeared to shift from circumferential to radial within any individual injector. Prior nanoSTAR™ testing had indicated that circumferential non-uniformity is much more harmful to emissions performance than radial non-uniformity. That principle seemingly held true during loop testing, as the restrictor plates clearly improved emissions performance over the baseline hardware.

### *Loop Test Summary*

A second round of engine tests of the nanoSTAR™ combustion system was completed successfully. The C-40 loop engine, a recuperated turbine, served as the evaluation vehicle. Ignition, acceleration, and pilot/main transitions were all smooth and repeatable. Acceleration to full-load engine speed was demonstrated several times and additional operating time was accumulated on the nanoSTAR™ hardware. All of these accomplishments added confidence that the surface-stabilized combustion system could be adapted to real gas turbine engines.

Performance with and without restrictor plates was compared. The restrictor plates impacted the distribution of air entering the injectors and improved emissions and stability performance. $NO_x$ emissions below 3 ppm and CO emissions below 15 ppm (both corrected to 15% $O_2$) were realized at simulated T-70 full-load engine conditions. These emissions levels were similar to those achieved consistently in single-injector nanoSTAR™ tests. Additionally, no significant combustion-driven pressure oscillations were encountered at any point during the tests. The test results support the hypothesis that a uniform premix is essential to achieving emissions targets. An improved premixer design that is less sensitive to airflow non-uniformities should allow the nanoSTAR™ combustor to meet all critical performance criteria on the T-70 engine.

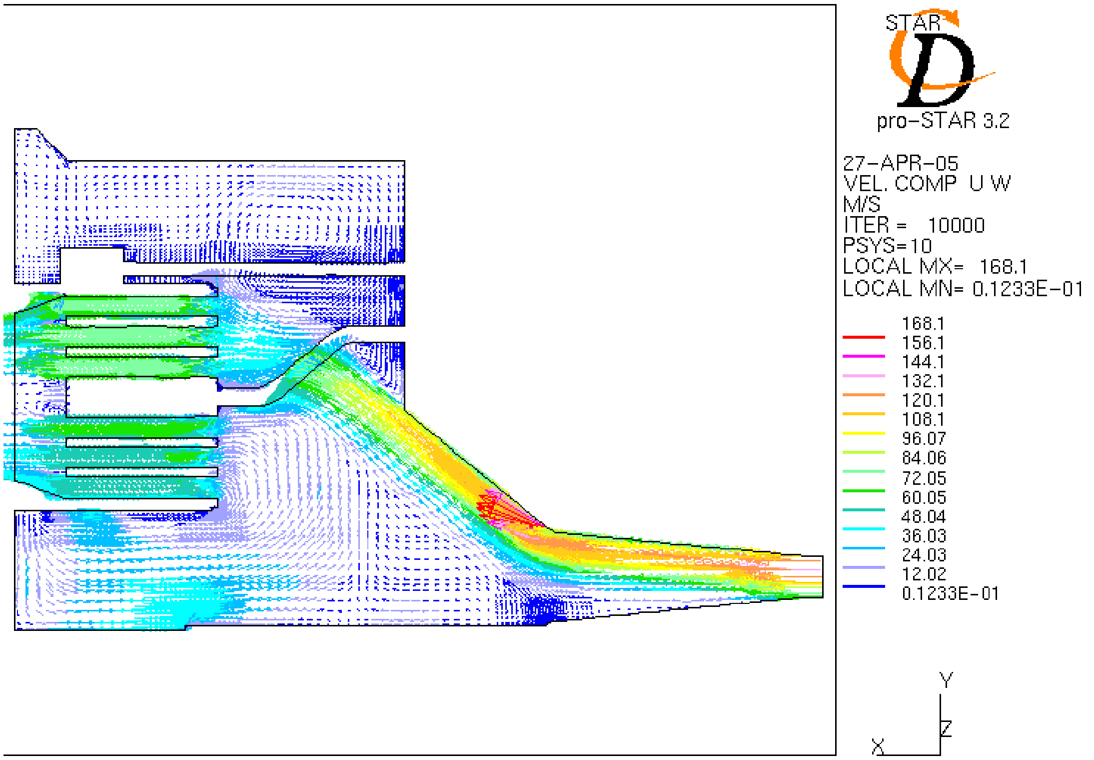
## 4.3. Production Combustion System Design Study and Testing

Design analyses and testing efforts completed in addition to the initial T-70 engine evaluations helped define the preferred configuration for the T-70 gas turbine using the nanoSTAR™ technology. Salient information from the tasks performed under this activity is described in the sections below.

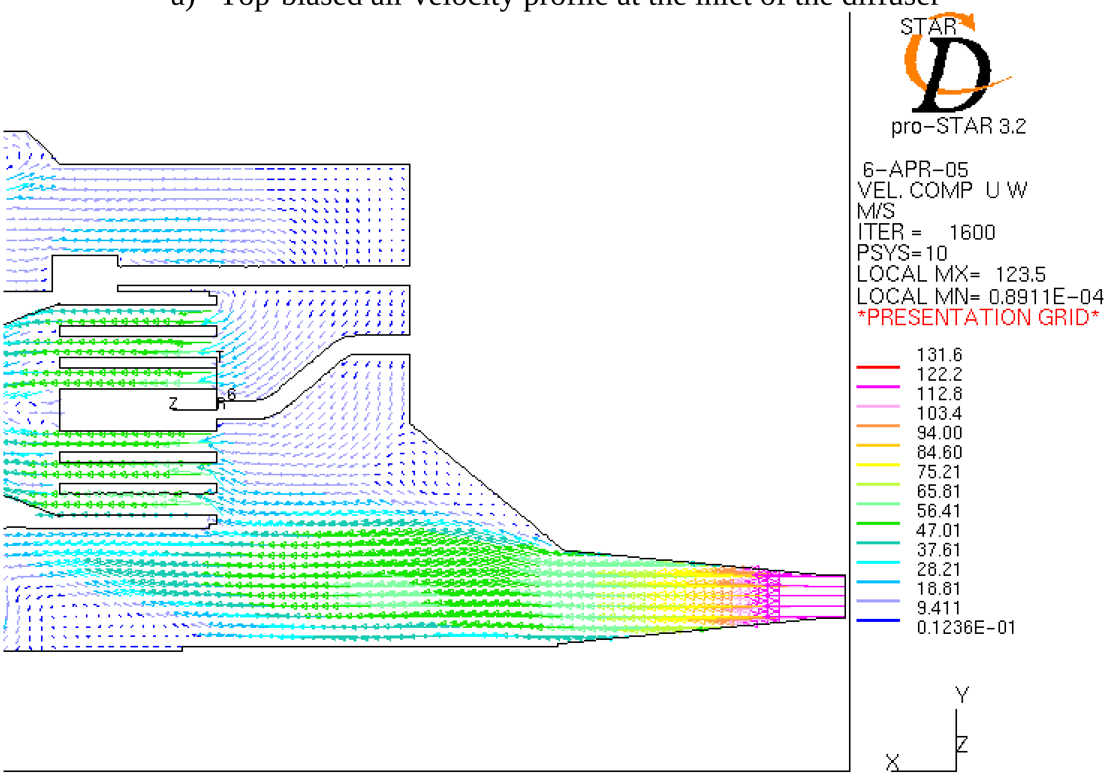
### *4.3.1. Lessons Learned from the T-70 Engine Test*

Poor emissions observed in the initial T-70 engine tests highlighted the sensitivity of the proof-of-concept premixers to airflow distribution in the upstream combustor plenum. The hardware was initially developed and tested in rigs that did not include a close-coupled compressor. As such, the flow distribution at the inlet to the mixers was highly uniform and not representative of real-engine conditions. On-engine measurements indicated that poor airflow distribution could result in a spread of as much as 800°F in reaction temperature over the surface of each individual injector. Such disparity dramatically affects emissions and may potentially put the burner hardware at risk. Burners are made of thin sintered metal fibers with low thermal capacity, hence they are poorly equipped to tolerate high-temperature excursions without experiencing damage. Operating the injectors with a poor mixture distribution ultimately places them at risk of running locally hot.

While the root cause of the poor air flow distribution was not unforeseen, the magnitude observed was likely larger than predicted by CFD analyses. Figure 31 depicts the air flowfields predicted in the engine. However, it should be noted that the accuracy of these calculations was largely unknown prior to the activities described below. Analysis indicated that the predicted flowfield was very sensitive to the assumed velocity profile at the inlet of the diffuser. Very limited velocity data were available at the time to support the CFD calculations.




a) Top-biased air velocity profile at the inlet of the diffuser




b) Uniform air velocity profile at the inlet of the diffuser

**Figure 31. Flowfields Predicted by CFD**

It now appears that the best approach to implementing nanoSTAR™ on the T-70 engine would be to work within the geometric constraints of the existing production system. Compared to the proof-of-concept nanoSTAR™ premixers, production premixers would be smaller in diameter and located further downstream from the diffuser. Both of these attributes would likely lead to improved airflow uniformity at the inlet to the injectors and thus enhance emissions performance.

### 4.3.2. Single-Injector Reaction Structure Assessment

In order to better comprehend the impact of poor airflow uniformity, single-injector tests were conducted simulating the airflow maldistribution observed in the engine tests. Rig airflow was artificially biased using perforated plates with varying hole sizes to mimic the flow distribution observed in the engine. Tests were conducted at ambient pressure with simulated full-load inlet air temperature (800°F), and a mean flame temperature of 2750°F. The tests clearly demonstrated that poor flow distribution at the inlet of the premixer tends to persist through the burner and result in a flame temperature gradient across the surface. Figure 28 shows this gradient with the top half of the injector burning hot and the bottom half burning cold. This type of reaction structure would explain the high CO and high $NO_x$ emissions observed in the engine tests—the cold portion of the burner produces high CO, while the hot portion produces high $NO_x$. These single-injector assessments highlighted the need to more closely study the flow distribution in the engine combustor plenum.

### 4.3.3. Combustor Plenum Flow Studies

Studying the flow field in the combustor plenum involved creating a scaled (1.5X) 30°-sector model of the engine diffuser, fuel-air mixer, and combustor dome. Belcan Corporation was subcontracted for their expertise in engine aerodynamics and experimentation to team up with Solar Turbines and work on this effort. The study involved:

- Designing and building a realistic fiberglass model with visual and instrumentation access
- Testing the model at simulated engine conditions to characterize flow field distribution, velocities, and pressures
- Identifying hardware changes that improved flow uniformity at the inlet of the premixers

Tests with baseline geometry showed that the majority of the flowfield followed a circuitous path around the premixer before entering it (see Figure 32).

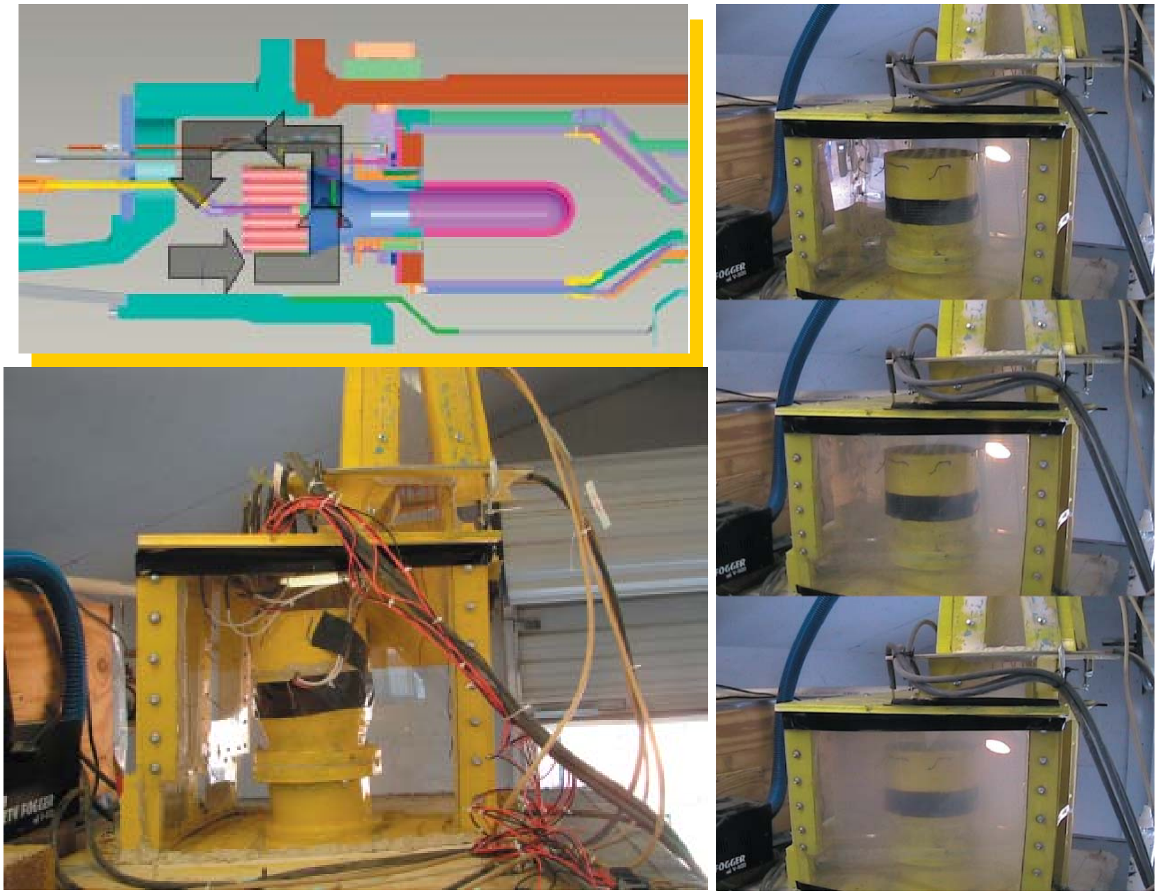


**Figure 32. Plenum Flow Studies**

Unlike the CFD results, these test results showed no sensitivity to the velocity profile at the inlet of the diffuser. The experimentally observed flow path agreed only with CFD analyses performed with a uniform velocity profile at the inlet of the diffuser (Figure 31b). Once the baseline flow patterns were characterized, emphasis switched to identifying modifications to the geometry that would improve flow distribution.

Two options for improving the flowfield at the inlet of the mixers were selected based on design simplicity and the predicted magnitude of additional system pressure drop. These options were (a) the use of a perforated plate at the inlet of the premixers to make them less sensitive to inlet pressure variations, and (b) the use of a deflector plate, or "visor", near the top of the premixers to improve the pressure distribution at the inlet. A redesign of the T-70 compressor diffuser was considered, but ultimately rejected due to the major design effort that would be involved.

The modifications attempted to reduce the flow variation at the inlet of the premixers to less than 3%. This target is derived from the desire to maintain flame temperature uniformity over the burner surface to within 50°F. Tests with the perforated plate met the uniformity target with generally lower pressure loss than the visor. The visor tended to deflect the flow to the sides of the mixer and resulted in higher pressure loss.

### 4.3.4. *Loop Engine Evaluations*

The flow studies described above served to define the optimum perforated ("restrictor") plate design to test on the engine. A modified Centaur 40 (C-40) recuperated engine was utilized for these evaluations due to its design flexibility and availability. The engine is configured with an external, side-mounted combustor arrangement that allowed testing of the existing T-70 nanoSTAR™ combustor on the smaller C-40 unit (see Figure 33). For this reason, the C-40 test rig is commonly referred to as the "loop engine". Testing on the loop engine also allowed the opportunity to further investigate the response of the nanoSTAR™ system to engine transient events such as startup, acceleration, and pilot/main transitions when entering and exiting low-emissions mode.

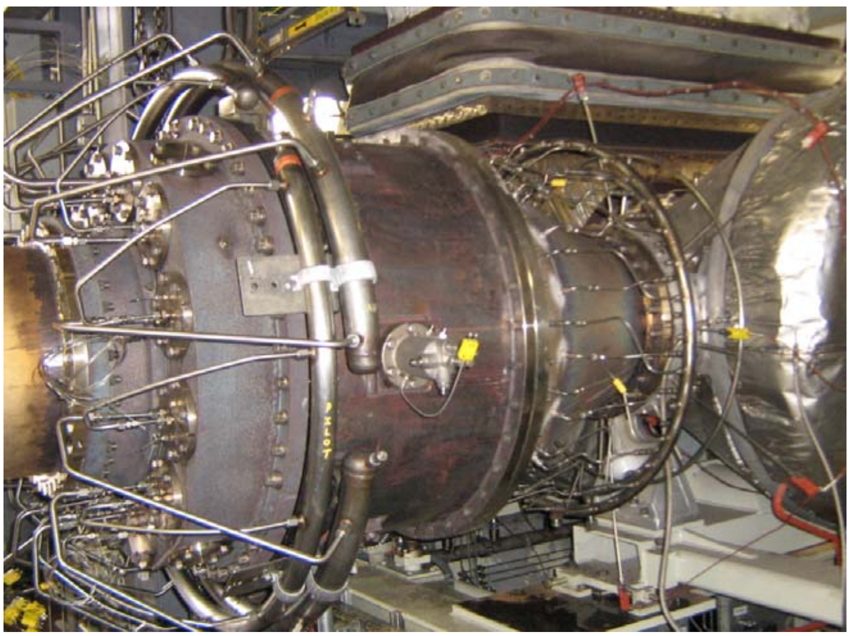


**Figure 33. C-40 Loop Engine**

Two separate loop engine tests were performed. The first test was completed with hardware identical to that used in prior T-70 engine tests. The second test was conducted with a set of perforated plates mounted at the inlet of each of the fuel/air premixers. In the second test, the restrictor plates improved the air distribution and resulted in $NO_x$ emissions below 3 ppm, with less than 10 ppm CO (both corrected to 15% $O_2$). $NO_x$ emissions were approximately 50% higher in the first test where the inlet airflow was not as uniform.

The loop engine tests demonstrated the importance of a uniform upstream air distribution in achieving ultra-low emissions. It is now deemed very likely that the unexpectedly high $NO_x$ emissions observed in the T-70 engine tests were the result of flow non-uniformities that develop as the compressor discharge flow expands into the combustor housing.

### 4.3.5. Preferred Embodiment for Integration

The above tasks served to define the preferred embodiment for integrating the surface combustion system into a production T-70 engine. It is now known that the proof-of-concept combustion system tested on the T-70 engine occupied too much space in the combustor plenum. For simplicity of integration, the preferred combustion system should employ the existing engine diffuser and combustor housing. To achieve this, the premixers need to be reduced in size and their inlets need to be located further downstream from the diffuser as illustrated in Figures 17 and 34. These design changes would help ensure a more uniform air distribution at the inlet of the injector and thus would improve overall nanoSTAR™ performance.

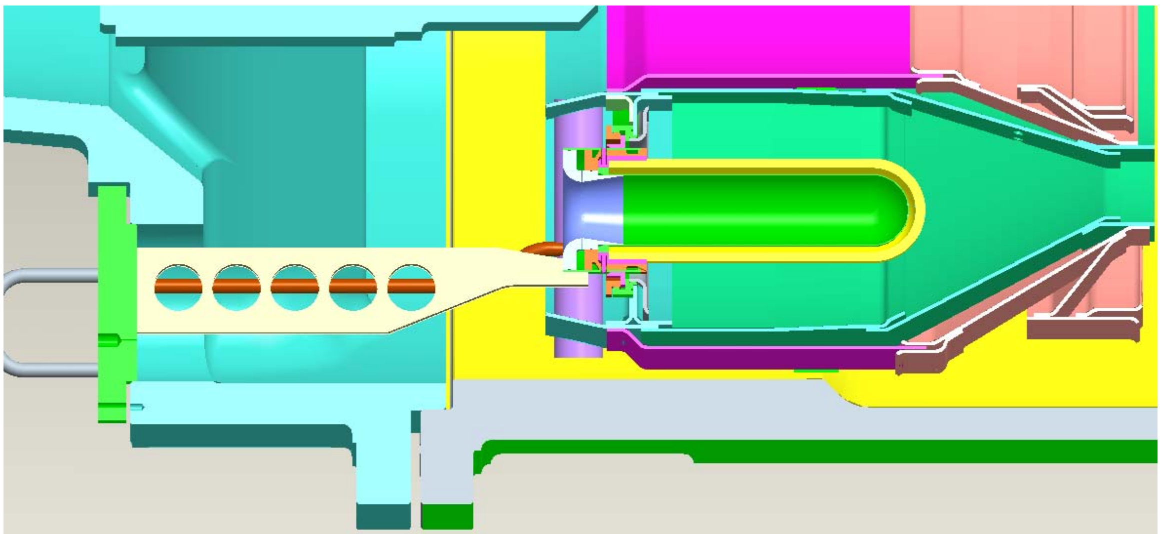


**Figure 34. Conceptual Next-Generation Axial System**

Design and preliminary testing of a next-generation premixer such as the one shown above have begun. Cold flow tests have measured adequate effective area, and initial mixing tests have shown promising performance. Optimizing the design of the next-generation premixer falls outside of the scope of this program and would likely need to be repeated whenever adapting the nanoSTAR™ combustion system to a particular engine model.

## 4.4. Combustion System Technology Assessment and Down Select

As part of the technology down select process, the Alzeta nanoSTAR™ combustion technology was evaluated in the same eight areas used to assess the lean catalytic system. The assessment results are highlighted in Table 7. The comparative assessment of the nanoSTAR™ and lean catalytic technology has already been presented in Table 3. As discussed earlier, further work on the CESI lean combustion system stopped after completing Phase I of the program.

**Table 7. Assessment of Surface Combustion System Commercialization Risk Factors**

(Green = Low, Yellow = Medium, Red = High)

| RISK FACTOR | RISK LEVEL | COMMENTS |
|---|---|---|
| SUB-2.5 PPM NOX CAPABILITY | Y | Emissions 1 to 2 ppm higher than catalytic system |
| PROJECTED PRODUCT COST | G | Low cost. Potentially lower than current DLE injectors. |
| EASE OF INTEGRATION | G | Straight-forward integration into annular geometry |
| DEVELOPMENT RISK | Y | May require modest increase in combustor volume and housing. |
| DUAL FUEL CAPABILITY | R | Liquid fuel capability not demonstrated. Propane backup a possible but unproven option. |
| DEMONSTRATED DURABILITY | R | Long-term durability needs to be demonstrated in field test. |
| IMPACT ON PACKAGE COMPLEXITY | G | No significant impact on package. |
| RETROFIT POTENTIAL | Y | No major hurdles to retrofit. |

In contrast to the PCI RCL combustion system, Alzeta's nanoSTAR™ technology is better positioned for engine adaptation (see Table 8). As discussed previously, Phase II focused on advancing the Alzeta surface combustion system to engine testing. In parallel, Solar Turbines continued to work with PCI on evolving the RCL technology. However, to date the PCI system has not reached full-scale rig evaluation, and will not likely reach an engine test. While progress has been done to reduce the size of the RCL injectors, the injectors will not fit existing T-70 engines while allowing adequate air distribution to premixers. The size of the injectors involved will require a new canted combustion system, and hence costly development of a canted combustor, a new combustor housing, and a new compressor diffuser. In addition, little is known about the long-term durability of the RCL injectors at engine conditions, and PCI may lack resources required to bring the RCL technology to market.

**Table 8. Comparison of Combustion System Risks: RCL vs. NanoSTAR™**

(Green = Positive/Low Risk, Yellow = Neutral/Medium Risk, Red = Negative/High Risk)

| | RICH/LEAN CATALYTIC | SURFACE COMBUSTION |
|---|---|---|
| SUB-2.5 PPM NOX CAPABILITY | G | Y |
| PROJECTED PRODUCT COST | Y | G |
| EASE OF INTEGRATION | Y | G |
| DEVELOPMENT RISK | R | Y |
| DUAL FUEL CAPABILITY | R | R |
| DEMONSTRATED DURABILITY | R | R |
| IMPACT ON PACKAGE COMPLEXITY | Y | G |
| RETROFIT POTENTIAL | R | Y |

### 4.4.1. $NO_x$ Emissions Capabilities

Testing has shown that the surface combustion technology produces NOx emissions that are 1 to 2 ppm higher than the catalytic systems. This results in emissions that are very near the program target. Thus, there is moderate risk that the technology will not meet the program goals on a production basis when manufacturing variations and site conditions that may affect emissions performance are considered.

Potential improvements in $NO_x$ emissions may be possible through improved premixer design and better airflow control upstream of the combustor (better uniformity among premixers and across each individual premixer).

### 4.4.2. Durability

Significant efforts have gone into evaluating the nanoSTAR™ burner durability. These include conducting rig tests to assess elevated temperature endurance, cyclic ignition/extinction performance, and material oxidation. In addition, the latest engine tests have demonstrated good short-term durability at actual engine conditions. While the information gathered is valuable, it is not enough to definitively determine if the injectors will have a life greater than 8000 hours in practical engine applications.

Evidence that supports the potential for the burner life to exceed 8000 hours includes:

- Rig tests showing that under design conditions (flame temperature of 2750°F) the burners will operate with surface temperatures below 1450°F

- High temperature endurance tests demonstrating that burners can tolerate excursions to a flame temperature of 3400°F for durations on the order of 50 hours without suffering any detectable damage
- Oxidation rate test data supporting a model that predicts burner life will exceed 8000 hours

Nonetheless, the following are still of concern:

- The potential of surface plugging by particulates in the air, which may lead to localized overheating of the burners and eventual failure. Inlet filters may reduce the risk of harmful plugging, but increased maintenance needs would hurt marketability.
- The potential effect of fuel impurities and combustion products on corrosion/oxidation rates
- The potential impact of mechanical engine vibrations on material integrity

All-encompassing long-term rig durability tests are impractical. With the information currently known, the next logical step to assess durability would be a long-term engine field test.

### 4.4.3. Combustion System Integration

Of the combustion systems evaluated, the nanoSTAR™ combustion system requires the lowest level of engine modification. The injectors marry well with the T-70 annular combustor geometry, and a design that would not require modification to the engine diffuser or combustor housing has been defined. The combustor size may need to be increased to provide more combustion residence time for CO burn-out. However, the combustor may not need to be canted as previously believed. This leads to a significant advantage in terms of engine retrofit, as any major design changes to the existing engine hardware are eliminated. Minimal external package modifications would likely be limited to the installation of new fuel lines.

### 4.4.4. Manufacturing Status

Alzeta has well-documented and consistent processes in place to produce the surface-stabilized burners. With extensive manufacturing facilities in Santa Clara, California, they are well poised to meet manufacturing needs for initial product rollout. Furthermore, their processes are easily expandable to produce incrementally larger quantities of burners.

Premixers, pilot modules, and combustors would be manufactured by Solar Turbines. The current designs would utilize conventional manufacturing facilities already in place at Solar Turbines' San Diego facility. As with other new product introductions, some production-quality tooling may be needed to streamline manufacturing.

### 4.4.5. Projected Cost

Of the three technologies considered, the surface combustion technology has the lowest first projected cost. Projections of the relative costs of the candidate combustion technologies were discussed earlier and are shown in Table 4.

## 4.5. Technology Transfer (Task 2.6)

Please see Appendix II-A.

## 4.6. Production Readiness Plan (Task 2.7)

Please see Appendix II-B.

# 5.0 Conclusions and Recommendations

Engine tests of the nanoSTAR™ technology showed promising results. Two rounds of engine tests were conducted: The first in a T-70 engine, and the second in a unique Centaur 40 (C-40) recuperated engine that enabled the same T-70 nanoSTAR™ system to be installed.

Tests on the T-70 engine were limited to 50 percent load due to an internal air leak in the engine that prevented further increase in load without reaching primary zone reaction temperature limits. The tests demonstrated:

- Acceptably low component temperatures and appropriate combustor exit gas temperature distribution.
- The ability of the surface combustion system to handle transient engine operation without suffering any damage.
- An engine control algorithm delivering smooth and safe engine operation throughout startup, acceleration, and steady-state testing.

More importantly, the initial T-70 engine tests highlighted the importance of air flow distribution in the combustor plenum. On-engine measurements indicated that poor airflow distribution could result in a spread of as much as 800° F in reaction temperature over the surface of each individual injector.

Detailed studies later confirmed that the airflow in the combustor plenum followed a roundabout path before entering the premixers with a wide variation in distribution. Increasing the pressure loss at the inlet to the premixers with the use of a perforated restrictor plate significantly improved the mixer performance.

Subsequent tests on the C-40 loop engine, with perforated restrictor plates installed to improve the uniformity of the air flow, demonstrated $NO_x$ emissions below 3 ppm with less than 10 ppm carbon monoxide (CO) (both corrected at 15 percent $O_2$) at T-70 full-load inlet temperature (800° F) and C-40 maximum operating pressure (7.5 atm). During these tests, the nanoSTAR™ system once again met critical engine operating criteria. Component and gas temperatures were within design limits, dynamic pressure oscillations were negligible, and the system handled engine-transient events without any hardware degradation.

To date, the Precision Combustion two-stage catalytic system has not reached full-scale rig evaluation, and will not likely reach an engine test. While efforts have been made to reduce the size of the injectors, the injectors will not fit existing T-70 engines while allowing adequate air distribution to premixers. The size of the injectors will require a new canted combustion system, and hence costly development of a canted combustor, a new combustor housing, and a new compressor diffuser. Furthermore, little is known about the long-term durability of the injectors at engine conditions, and Precision Combustion may lack resources required to bring the rich/lean, two-stage catalytic technology to market.

Further work to assess long-term durability is required in order to declare the technology market-ready. Concerns about plugging, mechanical vibrations, and fuel impurity effects would be best addressed in field evaluations. After developing adequate field-ready premixers, the next logical step for the evolution of this technology would be a long-term engine field test.

# 6.0 References


Greenberg, Steven and Neil McDougald. 2005. *Ultra-Low $NO_x$ Combustion System for a 13.5 MW Gas Turbine Generator—Final Report.* California Energy Commission, PIER Engergy-Related Environmental Research.

Greenberg, S. J., "Low NOx Gas Turbine Combustors for Distributed Power Generation," report to the California Energy Commission, contract number 500-97-031, ALZETA Corporation, March 2000.

2. McDougald, N. K., "Development and Demonstration of an Ultra-Low $NO_x$ Combustor for Gas Turbine Engines," report to the California Energy Commission, contract number 500-00-004, ALZETA Corporation, December 2003.

# 7.0 Glossary

| Acronym | Definition |
|---|---|
| AQMD | Air Quality Management District |
| CESI | Catalytica Energy Systems, Inc. |
| CO | Carbon monoxide |
| Commission | California Energy Commission |
| CPR | Critical Project Review |
| CTC | Caterpillar Technical Center |
| DLN | Dry Low $NO_x$ |
| DOE | U.S. Department of Energy |
| FeCrAlY | Metal alloy containing Iron, Chromium, Aluminum and Yttrium |
| nanoSTAR™ | Alzeta's DLN surface-stabilized technology |
| $NO_x$ | Oxides of nitrogen |
| $O_2$ | Oxygen |
| PCI | Precision Combustion Inc. |
| PIER | Public Interest Energy Research |
| ppm | Parts per million |
| psi | Pounds per square inch |
| SCR | Selective Catalytic Reduction |
| $SoLoNO_x$ | Solar Turbines Inc. DLN technology |
| Taurus 70 (T-70) | A 7.5 MW gas turbine manufactured by Solar Turbines |
| T-70C | T-70 turbine with a catalytic combustion system |
| UHC | Unburned hydrocarbons |
| ULN | Ultra-Low $NO_x$ |

# 8.0 Appendices

## 8.1. Appendix I-A: Preburner

## Appendix I-A: Preburner Design and Analysis

This appendix presents the design and analysis of the catalytic combustion system preburner, a critical system component. Experience has shown that any $NO_x$ formed in the preburner is largely carried through the catalytic reactor to the engine exhaust. As virtually no NOx is generated in the catalytic reactor itself, overall engine $NO_x$ is primarily a reflection of preburner $NO_x$ levels.

### Summary

The preburner design for Taurus 70 catalytic system (T-70C) has two axial stages of fuel injection. The requirement of a multi-stage preburner is driven by turndown capability demand based on extreme engine operating conditions. The number of injectors in the primary and secondary stages is eight and sixteen, respectively. The ratio of secondary to primary stage air split is 4.1 which is set by temperature rise requirement at 100 % load on a $120^0$ F day and $NO_x$ limit at 50% load on $0^0$ F day. Computational Fluid Dynamics (CFD) was used to evaluate reacting flow field for 100 % load standard day condition. The CFD analysis has shown that the preburner performance is expected to meet the design requirements. The actual performance of the preburner will be tested once the hardware is ready and results will be compared to CFD predictions.

### Introduction

CESI has successfully demonstrated implementation of Xonon 2.1 catalytic combustion system on a 1.4 MW Kawasaki gas turbine engine. The entire combustion system consists of four modules preburner, premixer, catalyst, and burn out. The main function of the preburner is to raise the compressor discharge air temperature above the catalyst light off temperature. The objective of this program is to scale Xonon 2.1 combustion system for Solar Turbines' Taurus 70 cold end drive gas turbine. This document explains the design methodology used to scale the preburner for T-70C. It also explains in detail results of the CFD work conducted on the preburner design.

### Design Approach

The philosophy used in T-70C preburner design was based on lessons learned at CESI during design and development of Xonon 2.0 and 2.1 combustion systems. A detailed thermodynamic cycle was first modeled for T-70C engine performance analysis. The model included three axial stages of air injection, primary, secondary, and dilution. The model also considered three stages of fuel injection, primary, secondary, and catalyst. Thermal quenching due to addition of catalyst fuel was accounted for via energy balance. The Taurus 70 engine performance data was obtained from FASTX engine model. The air splits between the various stages of the preburner are set by required temperature rise at engine operating conditions. Some of the design requirements of the preburner are given below;

Ambient operating range 0 to 120 $^0$ F

$NO_x$ emissions < 20 ppm @ 15 % $O_2$
Pressure drop < 1.3 %
Maximum wall temperatures < 1650 $^0$ F
Temperature uniformity ± 5%
Turndown 6.2 (ratio of maximum to minimum temperature rise)

A detailed description of various preburner stages is explained below. Some of the main features of the preburner are also summarized in Table 1.

## Primary Stage

The primary stage of the preburner is designed to start the ignition and provide the required temperature rise at design and off-design operating conditions with adequate blow out margin. The primary stage air flow is set to 3.8 % of preburner air flow which is based on minimum temperature rise required at full speed full load (FSFL) condition on a 120 $^0$ F day with a fresh catalyst. The primary zone volume is set to 325 in^3 to allow enough residence time required for carbon burnout at FSFL on a standard day. The volume is calculated starting from the dome to the beginning of outer liner wall expansion of the preburner, as shown in Figure 1. The primary stage injectors are designed to have cover plates at the air inlet side to allow flexibility of changing the effective area once the injectors are fabricated. These cover plates can be easily drilled with holes of various sizes to meet the required effective area. The design point effective area requirement based on pressure drop budget is 1.75 in^2. The number of injectors in the primary zone is set by maintaining circumferential gap of 3.48 in. The air/ fuel mixture is injected tangentially into the annulus in the primary zone. The primary stage annulus gap is set to 1.75 in. to avoid flame impingement on the inner liner wall. The injector diameter was set to maintain tube velocity of 65 ft/sec. to have an adequate flash back margin.

## Secondary Stage

The secondary stage of the preburner is designed to have maximum possible turn down capability. The secondary stage air flow split is established based on $NO_x$ emission requirement at 50 % load on a $0^0$ F day. Initially the secondary zone volume was set to 2260 in^3 based on 35 ms residence time requirement at part load on a cold day operation. The secondary zone volume was calculated from start of outer liner expansion to the first row of dilution holes. One of the main concerns about the secondary stage was poor operability due to large air split ratio between secondary to primary (Wa_secondary / Wa_primary = 4.1). In order to mitigate this risk, the secondary zone volume is increased to 3627 in^3 to have flexibility of splitting the secondary stage into two. This will require displacing every other secondary injector 2.5 to 3 times the axial slot length at the exit of the secondary premix tubes. The volume was thus increased to allow adequate residence in the tertiary zone for complete CO burnout. This will improve secondary zone efficiency and overall turndown capability of the preburner. However, the first preburner built will only have two stages. The number of injectors in the secondary zone is 16. Each injector has four axial slots that inject the mixture radially toward the inner liner wall. The injector size is set to maintain tube velocity of 68 ft/sec.

## Dilution Zone

The dilution air flow accounts for 80.5 % of the preburner total air flow. Both the outer and inner liner has two sets of 52 dilution holes. The ratio of air split between the outer and the inner liner was set to 1.2. Based on air flow rates the required effective areas for outer and inner liner dilution holes are 20.5 and 17.6 in^2, respectively.

| **Parameter** | **T-70C** | **Comments** |
|---|---|---|
| Primary air flow (%) | 3.8 | Based on minimum temperature rise requirement, FSFL 120 $^0$F |
| Secondary air flow (%) | 15.7 | Based on part load $NO_x$ limit on a cold day |
| Primary zone volume (in^3) | 325 | Based on 24 ms residence time at FSFL ISO day |
| Secondary zone volume (in^3) | 3365 | Allow flexibility to convert to a three stage design |
| Number of primary injectors | 8 | Based on circumferential spacing of 3.48 in. |
| Number of secondary injectors | 16 | Maintain tube velocity of 68 fps (ISO, FSFL) |
| Primary tube velocity (ft/sec.) | 65 | Injector diameter of 1 in. |
| Exit gas velocity (ft/sec.) | 54 | Requirement driven by premixer pressure drop budget |
| Outer to inner liner air split ratio | 1.2 | Based on liner cooling requirements |

**Table 1: Main features of the preburner**

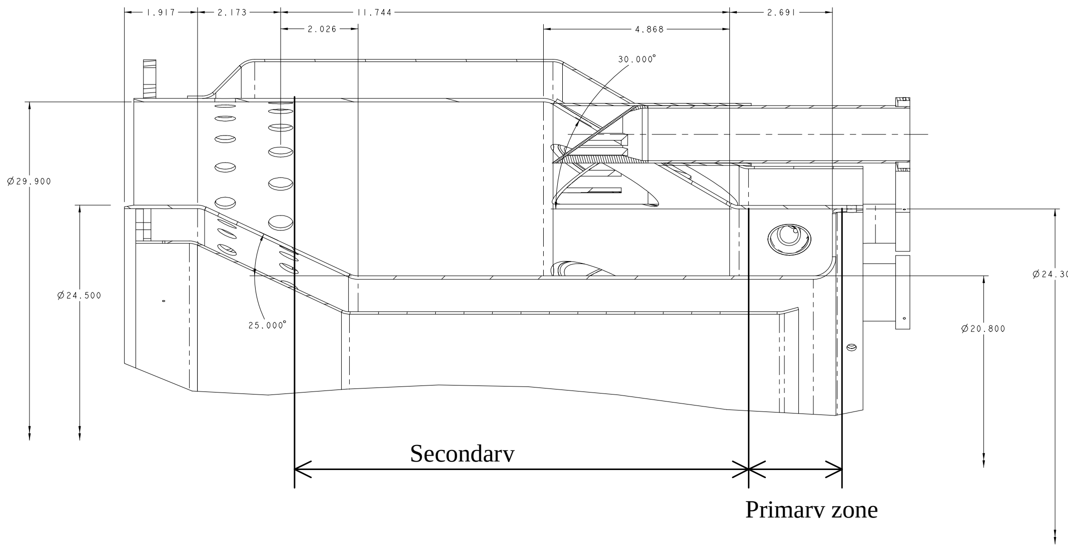



**Figure 1: Cross section of the T-70C preburner**

## CFD Analysis

The CFD work on the preburner was conducted by Combustion Science and Engineering (CSE). The boundary conditions chosen for FSFL ISO day are given in Table 2. For the sake of simplicity, natural gas was modeled as pure methane and perfect fuel/ air mixture was assumed at the primary and secondary injector tips. A $90^0$ bend was added at the preburner exit to simulate the preburner/ premixer interface.

| Parameter | Unit | Value |
|---|---|---|
| P2 | psig | 232.5 |
| T2 | $^0$F | 804 |
| Wa preburner | pps | 39.1 |
| Wa pz | pps | 1.49 |
| * WF pz | pph | 167.7 |
| Wa sz | pps | 6.12 |
| * WF sz | pph | 100.4 |
| Wa dilution inner liner | pps | 14.52 |
| Wa dilution outer liner | pps | 16.96 |

**Table 2: Boundary conditions used for preburner CFD analysis**

* Flow rates based on natural gas LHV is 941 Btu/cu.ft, M.W = 17.29 lbm/lbmol

**CFD Results**

The conclusions drawn from CFD analysis are summarized below;

1. Flow from primary tubes causes radial jets to penetrate into the primary combustion zone influencing the flow across the whole annulus as shown in Figure 2

2. Tangential jets set up gradient in swirl velocity such that highly swirl flow stays outer radial and flow with less swirl stays inner radial as shown in Figures 3 and 4

3. Swirling flow generates slight pressure gradient such that low pressure stays inner radial as shown in Figure 5

4. Low pressure inner radial region causes axial velocity along the inner radius to head upstream as shown in Figure 6

5. The secondary flow was painted with a passive scalar to determine its flow path. Figure 7 shows that flow that is red initially came from secondary tubes, whereas, flow that is blue was never in the secondary tubes. The results clearly show that flow from secondary zone is heading back into primary combustion zone. This will tend to dilute the primary zone with cooler secondary flow thus harming the turn down capability of the primary stage

6. The swirl intensity of flow leaving the primary combustion zone decreases as the combustor area increases due to expansion of outer liner wall as shown in Figures 8 and 9

7. The swirl structure stays intact until the flow is disrupted by the secondary flow injection as shown in Figure 10

8. A significant dilution jet penetration occurs in the dilution plane making the swirl non-existent as shown in Figure 11

9. A low axial velocity region exists behind the primary nozzle break through in the outer dilution flow passage as shown in Figure 12. This will tend to lower the backside heat transfer coefficient at that location. It is predicted that this particular location on the outer liner may create a local hot spot.

10. A complex three dimensional flow field is created in the secondary zone and at the preburner exit as shown by in-plane velocity plots in Figures 13 and 14

11. Temperature in the primary combustion zone is very uniform as shown in Figure 15. The primary tube flow can be seen by the lower temperatures at the outer radius

12. A radial temperature gradient exists at start of outer liner expansion just downstream of primary combustion zone. A lower temperature along the inner radial wall in Figure 16 confirms ingestion of secondary flow into the primary zone

13. Figure 17 shows axial temperature profile of the preburner in the direction of flow indicating three distinct temperature regions in the primary, secondary, and dilution zones

14. As expected, fuel conversion takes place rapidly in primary and secondary combustion zones as shown in Figures 18 and 19

15. The main heat release region in the primary combustion zone is outer radial as indicated by CO mass fraction in Figure 20

16. The preburner exit temperature profile shows a minimum of 825 $^{0}$F and maximum of 950 $^{0}$F as indicated in Figure 21

**Conclusions**

The CFD analysis has shown that overall performance of the T-70C preburner would be very similar to CESI's Xonon 2.1 design. The primary stage turndown from base load can be improved by reducing the amount of secondary air ingestion into the primary zone. This could be accomplished by reducing the annular gap in the primary zone. The improved turndown of the primary stage would allow it to operate at leaner condition thus producing lesser $NO_x$. The liner metal temperatures need to be verified during testing at locations in-line with the primary nozzle break through. This location will have lower backside heat transfer coefficients due to reduced velocity in the annulus. The secondary zone volume has been increased to allow splitting it into two stages, secondary and tertiary. This will tend to improve the combustion efficiency of the secondary stage at lean operating condition to provide better control during entire engine operating range.

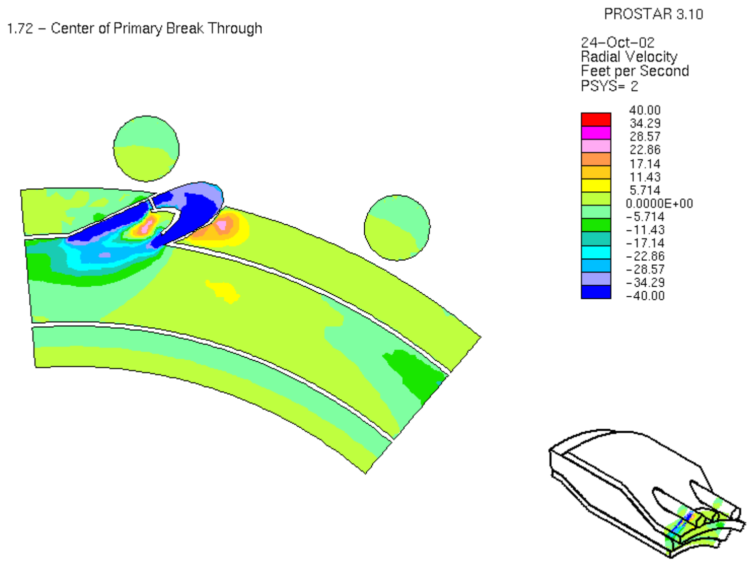



**Figure 2: Radial velocity distribution in the primary zone**

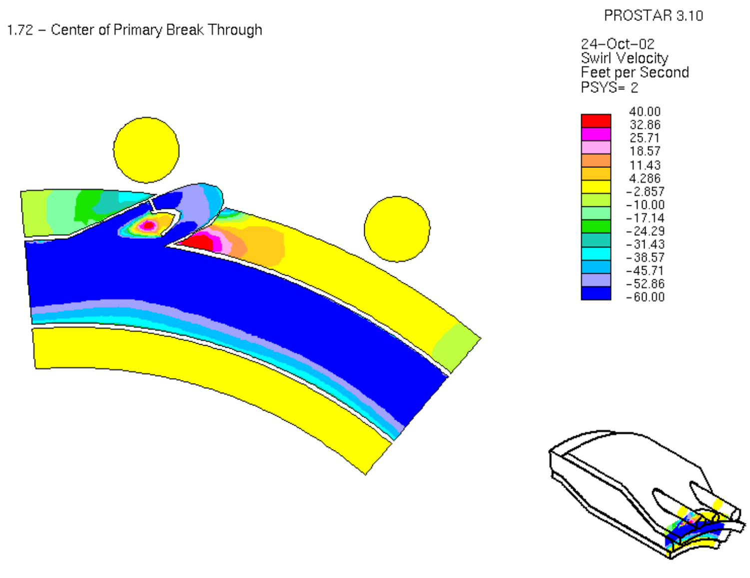



**Figure 3: Swirl velocity distribution in the primary zone**

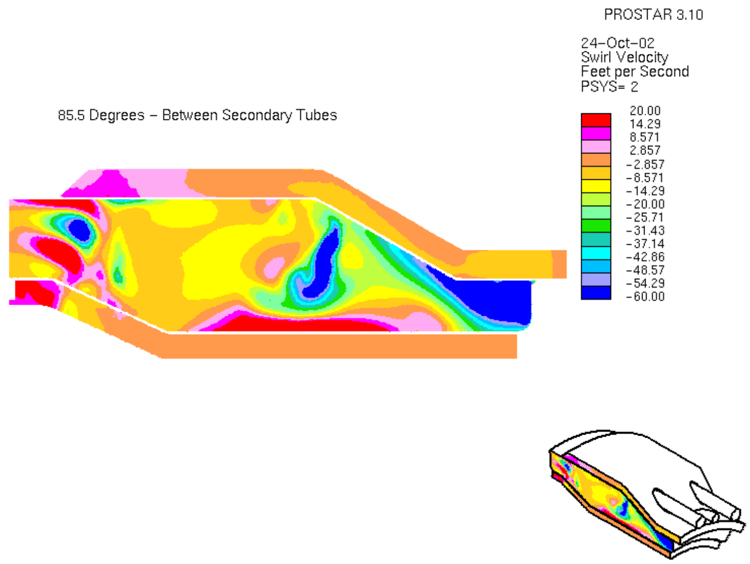



**Figure 4: Swirl velocity distribution in-between the injectors**

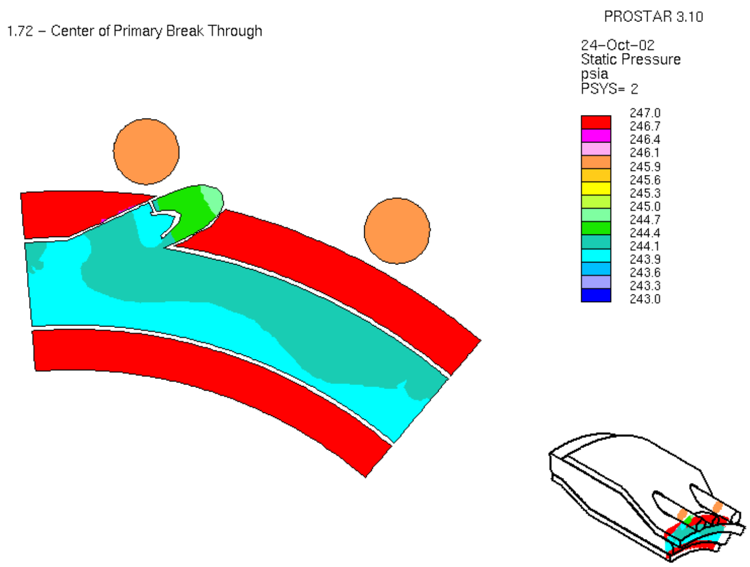



**Figure 5: Static pressure radial distribution showing primary jet breakthrough**

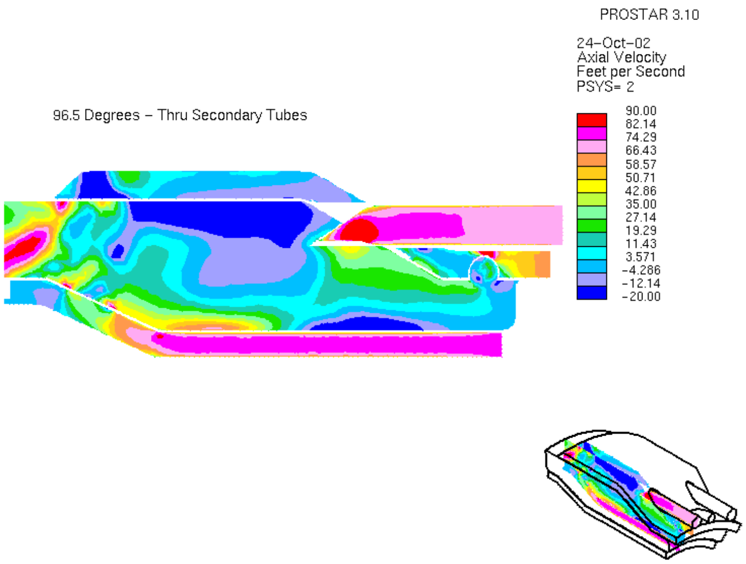



**Figure 6: Axial velocity distribution showing secondary jet breakthrough**

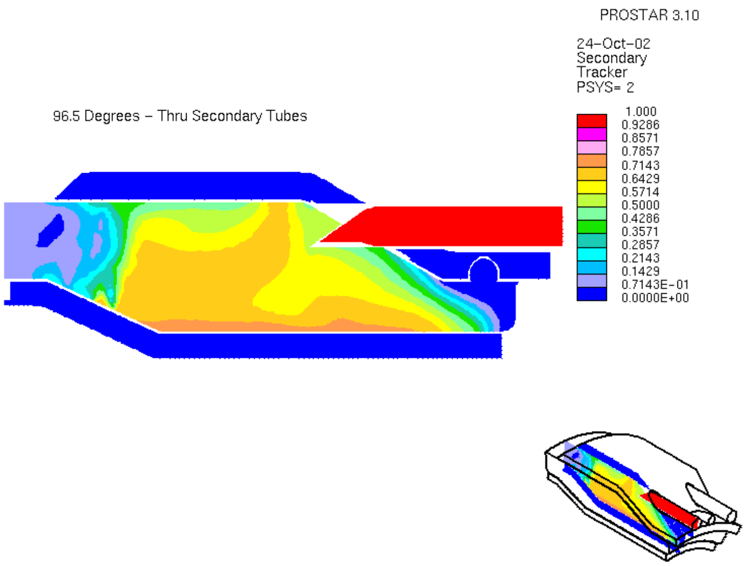



**Figure 7: Distribution of secondary flow into the preburner**

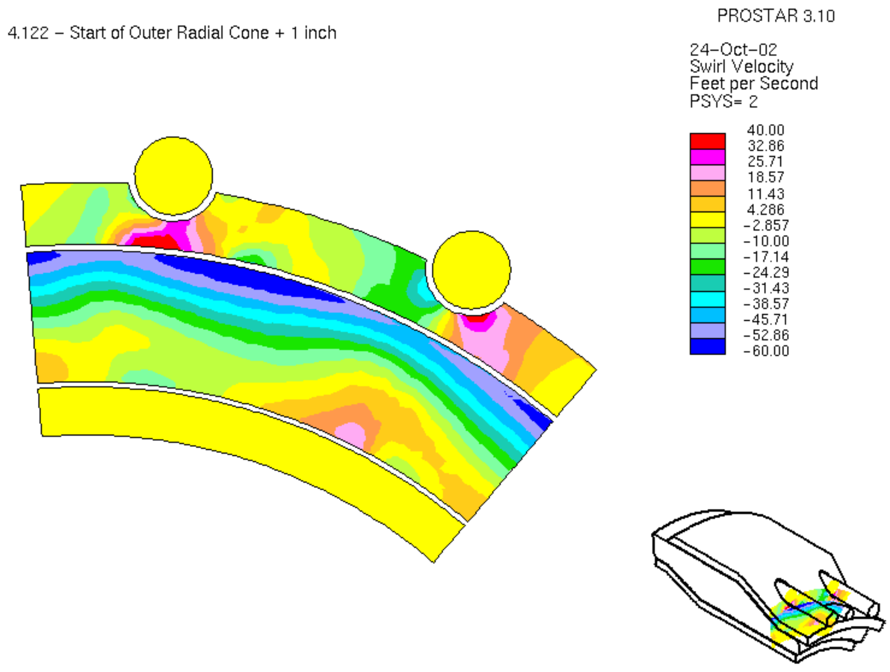



**Figure 8: Swirl velocity at one-inch downstream outer liner wall expansion**

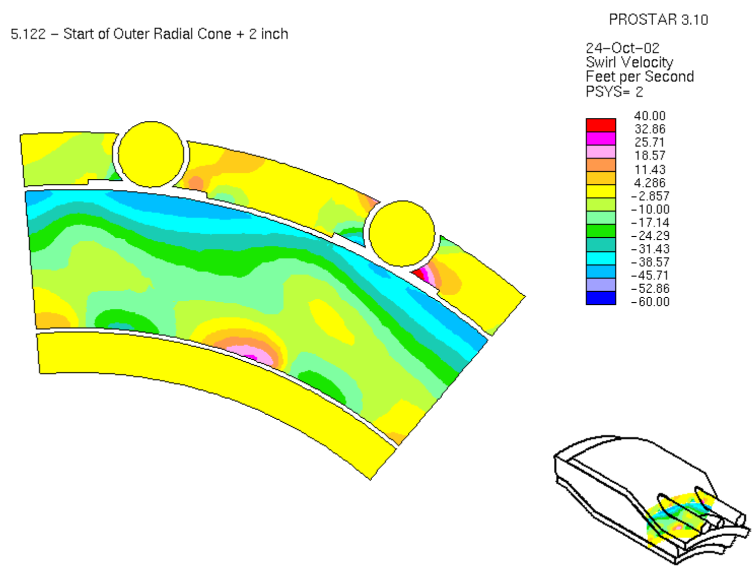



**Figure 9: Swirl velocity at two-inch downstream of outer liner wall expansion**

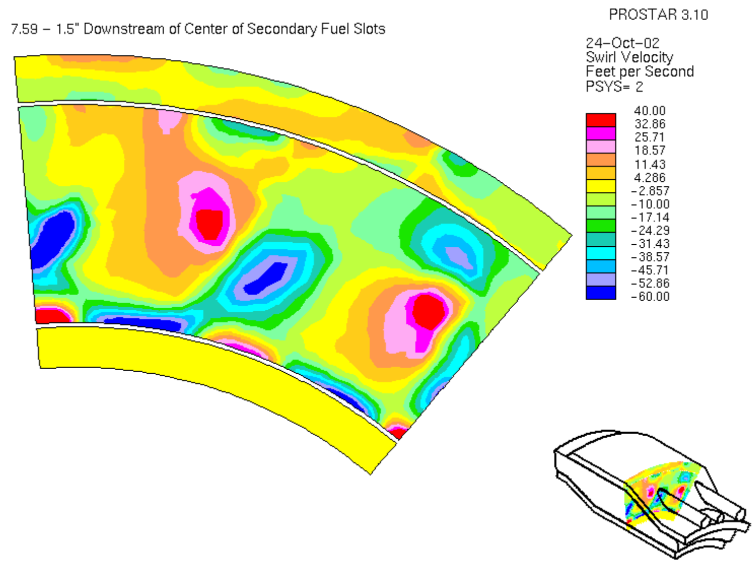



**Figure 10: Swirl velocity in the secondary zone**

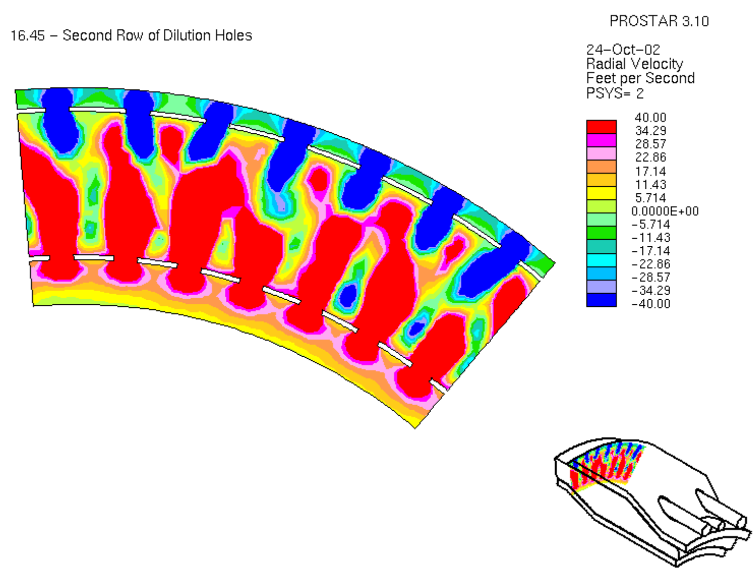



**Figure 11: Radial velocity indicating dilution jets penetration**

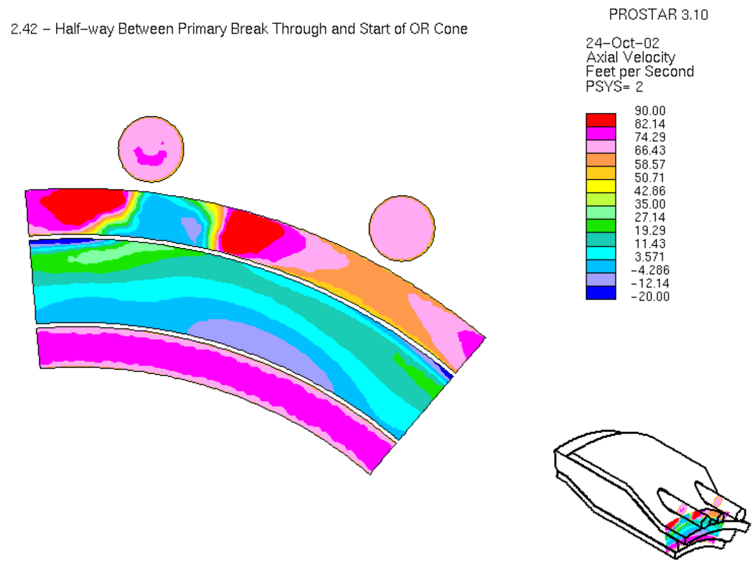



**Figure 12: Axial velocity distribution in the primary zone**

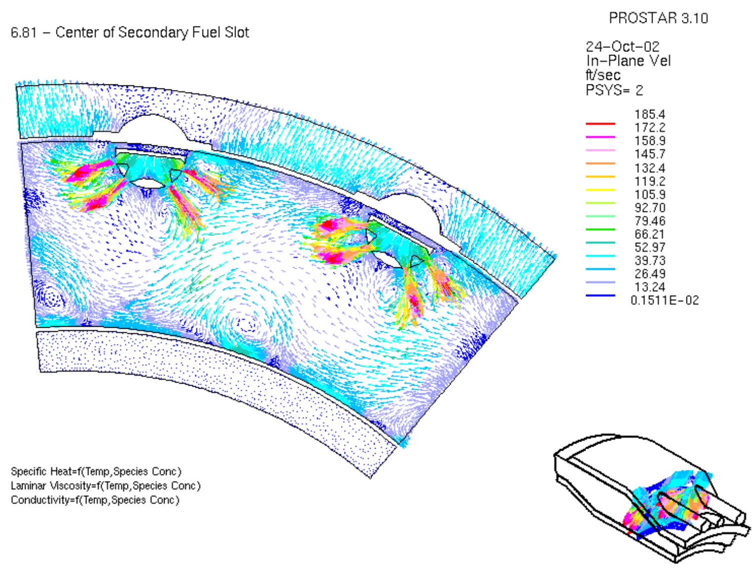



**Figure 13: In-plane velocity showing secondary jets**

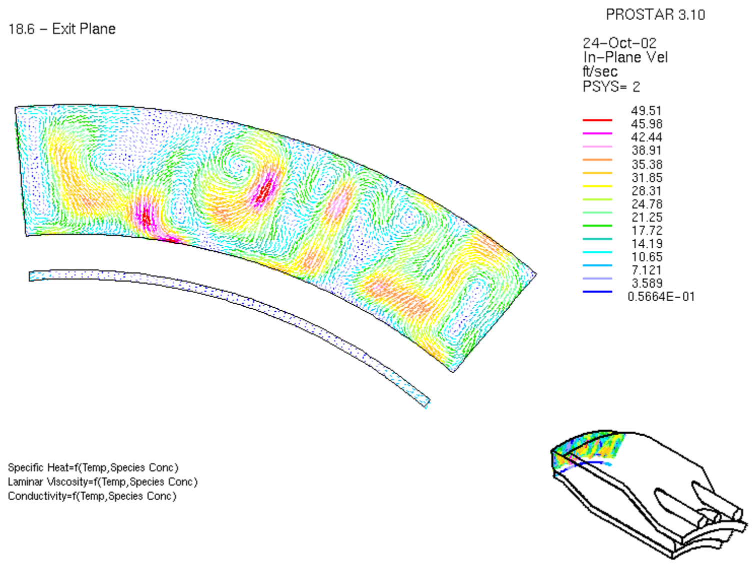



**Figure 14: In-plane velocity at the preburner exit**

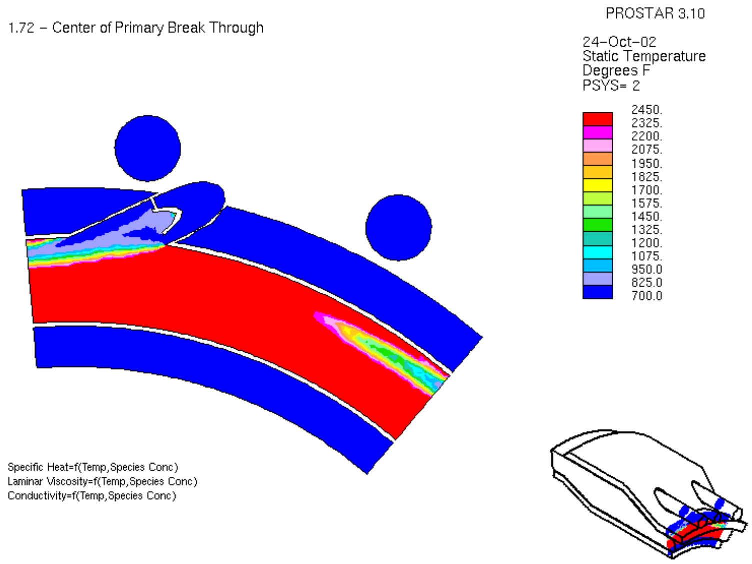



**Figure 15: Temperature distribution in the primary zone**

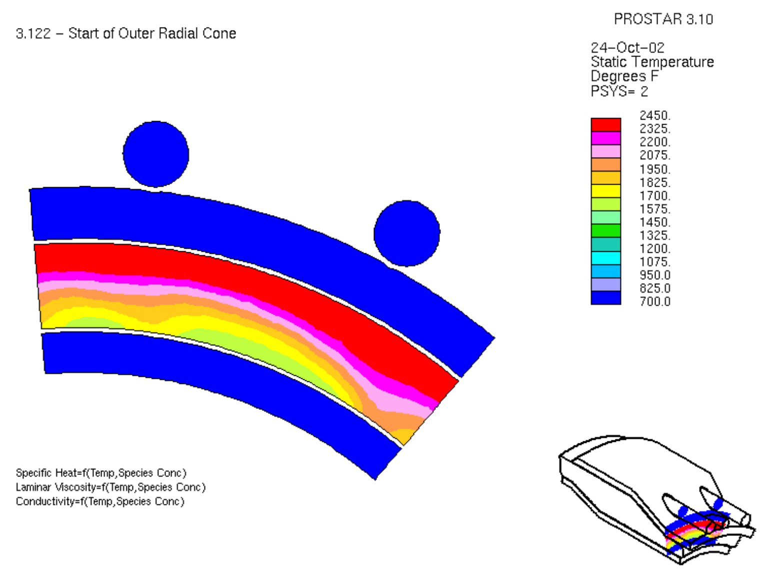



**Figure 16: Temperature distribution at start of the secondary zone**

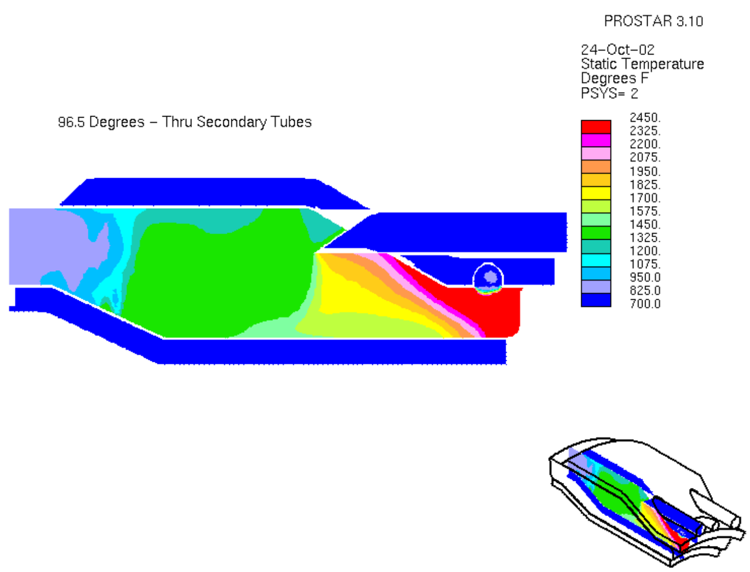



**Figure 17: Temperature distribution showing three distinct zones**

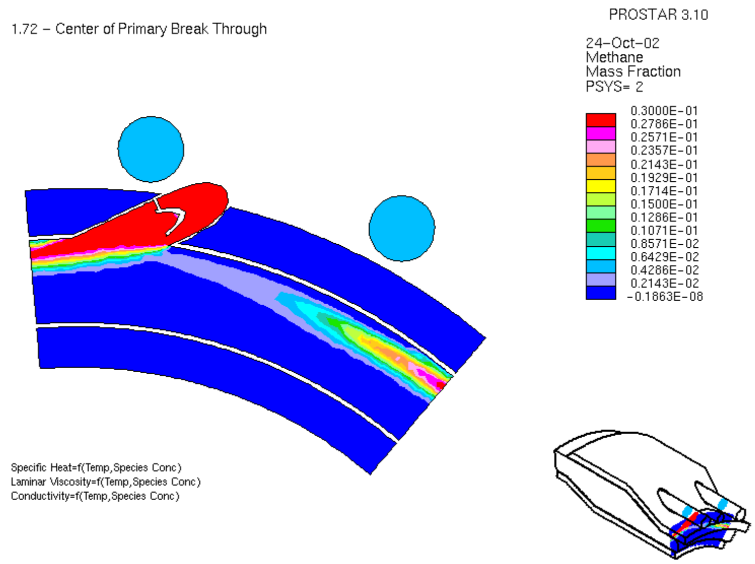



**Figure 18: Methane concentration in the primary zone**

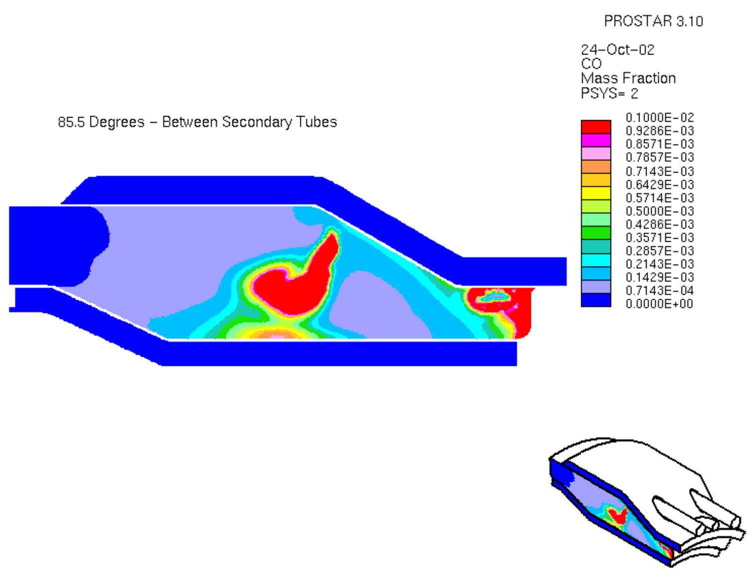



**Figure 19: CO mass fraction showing primary and secondary jets**

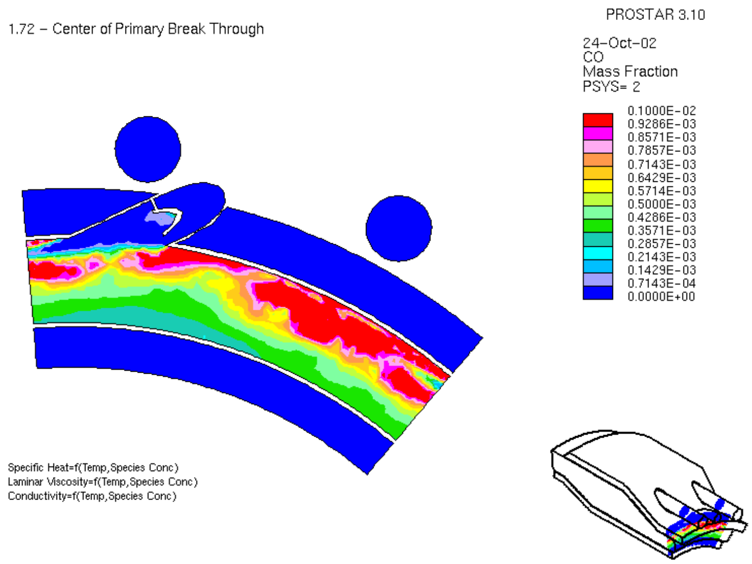



**Figure 20: CO mass fraction radial distribution in the primary zone**

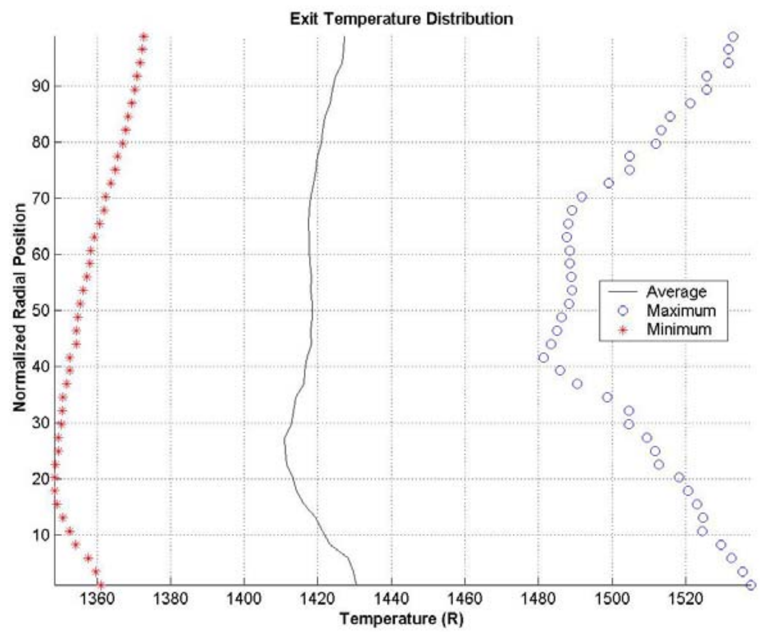



**Figure 21: Temperature profile at the preburner exit**

## 8.2. Appendix I-B: Scroll Assessment

## Appendix I-B: Taurus 70C Scroll Conceptual Design

**Introduction**
Solar Turbines is conducting a project with the California Energy Commission to evaluate the feasibility of a catalytic combustion system for its Taurus 70 gas turbine (7.5 MW). Such a combustion system is expected to provide ultra-low $NO_x$ emissions (below 3 ppmv at 15% $O_2$) on natural gas. This project is a joint effort with Catalytica Energy Systems Inc. (CESI).

At the present time, the catalytic combustion system technology is limited to cylindrical combustor configurations. The Taurus 70 production engine utilizes an annular combustor. Thus the integration of a catalytic system for the T-70 will require the design and development of a scroll that will connect the combustor exit (circular cross-section) with the turbine inlet nozzle (annular cross-section). The location and general geometry of the T-70C scroll are shown in Figs. 1 and 2. The scroll operates in an extreme environment as it ducts the combustor exit gas flow to the turbine. This flow is on the order of 2400F, much higher than can be tolerated by an uncooled metal structure. Scroll cooling will be a major challenge in the scroll development effort as scroll metal temperatures need to maintained below about 1600° F.

The scroll will have to meet performance goals in the areas of:

. maximum allowable pressure drop

. exit velocity circumferential uniformity

. wall temperatures (for acceptable durability)

. thermo-mechanical stresses due to temperature gradients at steady state and during engine transient operation.

In addition, the scroll configuration must physically fit within the space available in the T-70 engine, and the scroll must interface successfully with the catalytic combustor (upstream) and turbine nozzle (downstream).

Because of the complexity and projected high cost of the T-70 scroll, a two-step development process is being used. In the first step, the scroll effort was limited to a conceptual design study to assess the likelihood of meeting the various scroll design goals. This first phase has been completed in parallel with the design of the catalytic combustion system itself.

Once the combustion system is fabricated and tested successfully, the scroll development effort will then be advanced to a second step where the detailed design and fabrication of the scroll will be addressed. The scroll development must be completed to support on-engine testing of the catalytic combustor.

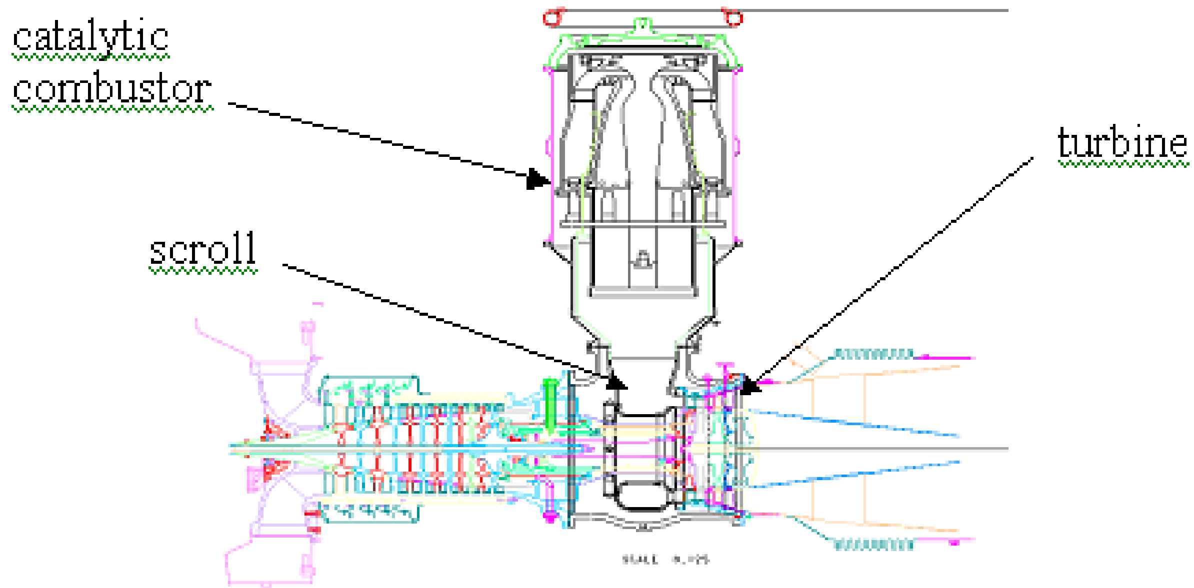



Figure 1. Catalytic Combustor- Fired Taurus 70

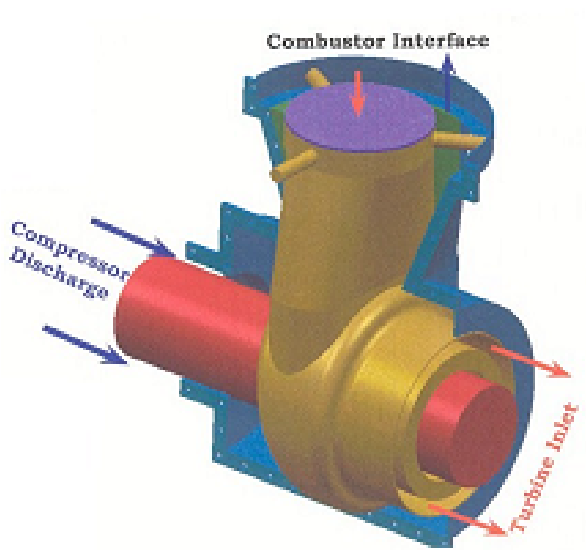



Fig. 2. Scroll Configuration

**Overview**
Solar Turbines worked with Belcan Corporation to assess several conceptual designs of scrolls for the catalytic T-70C, a plenum design (as opposed to a torus/"snail shell " design) was deemed to be the best choice considering the spectrum of design considerations associated with the scroll. Depictions of the scroll and scroll housing recommended for the T-70 are shown in Figs. 3A and B. The scroll housing will be fabricated in two parts to facilitate assembly. Analytical assessments and flow testing of a one-quarter scale plastic model (Fig. 4) were conducted to optimize (at this conceptual stage) the final scroll geometry.

Of particular importance in the analytical assessments was the heat transfer analysis. A prime goal was to determine if sufficient cooling of the scroll could be accomplished with the available air flow. Heat transfer analyses and stress analyses were performed at a level sufficiently detailed to allow selection of a preferred conceptual design. It was determined that although the scroll cooling requirement will be a challenge, there is adequate air available to meet the design goal of 1660 F maximum scroll temperatures.

The scroll will require fins on the outside surfaces to enhance the external surface heat transfer flux. Figure 5 shows the general orientation of the cooling fins. The ribs are generally aligned with the cooling flow streamlines as determined from the model flow visualization study.

## Scroll Costs

The geometric complexity and the need for cooling fins on the exterior of the scroll suggest that the scroll would best be made as a casting. Similarly, the external pressure casing is assumed to be a cast part.

To support cost estimates of the entire combustion system, Solar Turbines worked with one of its casting suppliers to develop order-of magnitude estimates for the scroll and the two split housing components (Fig. 6). Preliminary estimates for tooling, a first article and parts in full production are presented in Table 1. These estimates do not include Solar Turbines labor required to develop the final scroll design.

Table 1. Estimated Vendor Costs for Scroll and Split Casing
Tooling and Production

| Task | Scroll | Split Casing (2 pieces) |
|---|---|---|
| Non-Recurring Engineering | $334,000 | $526,000 |
| Tooling | $605,000 | $1,025,000 |
| 1st piece | $43,000 | $98,000 |
| 50th piece | $32,000 | $89,000 |

It should be kept in mind that these estimates are based on a conceptual design and will vary as a detailed design is developed. The high costs of development for the scroll and housings validate the project strategy whereby the combustion system performance is validated before addressing the detailed scroll design. The scroll conceptual design study, however, does indicate that the development of the T-70 scroll is feasible in light of the available cooling air and the space available within the engine.

Fig 3A. Final Scroll/Housing Conceptual Design

Fig 3B. Scroll Conceptual Design (One-half of Housing Removed)

Figure 4. Scroll Model Used for Flow Studies

Fig. 5 Configuration of Scroll Cooling Fins Based on Cold Flow Studies

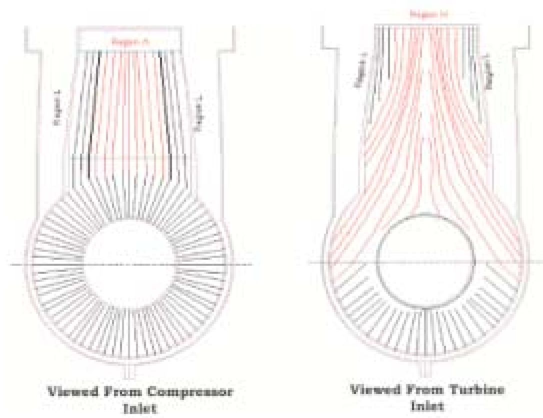



Fig 6A. Downstream Section of Scroll Housing

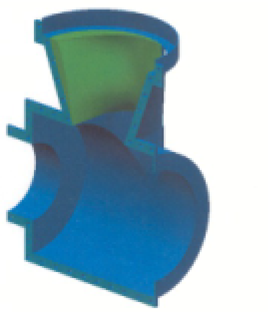


Fig 6A.
Downstream
Section of Scroll
Housing

Fig 6B. Upstream
Section of Scroll
Housing

## 8.3. Appendix I-C: Component Flow Tests

Appendix I-C: Component Flow Testing

## 1.0 Introduction

This document explains in detail the "cold flow" results obtained from tests conducted on various components of the Taurus 70 catalytic combustion system. The tests, for the most part, were conducted at Solar's injector and liner cold flow (non-combusting) test facilities. The primary, secondary, and premixer fuel injectors were individually flow tested to quantity pressure drop characteristics and part-to-part variation. The inner and outer liners for the preburner along with the burnout zone external cooling flow were also tested to ensure they meet pressure drop requirement.

## 2.0 Objective

The main objective of this series of tests was to ensure that individual components meet the design pressure drop and flow requirements before a final assembly was made. The components were tested both at sub-assembly level and as complete assemblies.

Testing involved installing the test pieces on a high precision flow facility maintained at Solar for production parts. Each test piece is then characterized by a series of flow versus pressure drop data points. These data are used to ensure that the test piece will flow the required amount of air (or fuel) at the design pressure drop. In addition, nominally identical parts can be compared to ensure that the parts have similar flow characteristics.

## 3.0 Test Results

### 3.0.1 Preburner

The fuel and airsides on all primary and secondary stage fuel injectors were cold flowed to quantify part-to-part variation. The first test was conducted on primary and secondary stage fuel muffs (plenums) by flowing air through the fuel passage. The results for the fuel side for the primary and secondary injectors are plotted in Figures 1 and 2, respectively. The acceptance criterion that all the injectors fall within -/+2 % of the deviation from the average was met with one exception. It was found that all the injectors were within -/+ 2 % except for serial number 11 for the secondary stage. This was a spare injector and will not be used in the final assembly of the preburner.

The second test was conducted on complete assemblies of the primary and secondary stage injectors. This included fuel muffs, premix injector tubes, and perforated plates at the inlet of the premix tubes. During this test the fuel side was blocked and air was flowed through the perforated plates and premix tubes. The results for these tests are shown in Figures 3 and 4. The acceptance criterion established for the complete injector assemblies was within -/+ 3 % from the average. As can bee seen, all the injectors had acceptable performance.

The preburner liners were also flow tested at various stages of the assembly. Initially the inner and outer liners were flow tested separately before the convectors were installed. This was done to make sure that air flow distribution between the outer and inner liners meets the design requirement. The results indicated that the inner to outer liner distribution ratio was acceptable at 1.17 compared to the design requirement of 1.2.

After the convectors were installed, the total liner effective area was measured by flowing air through the system. The effective area results from all preburner component tests are summarized in Table 1.

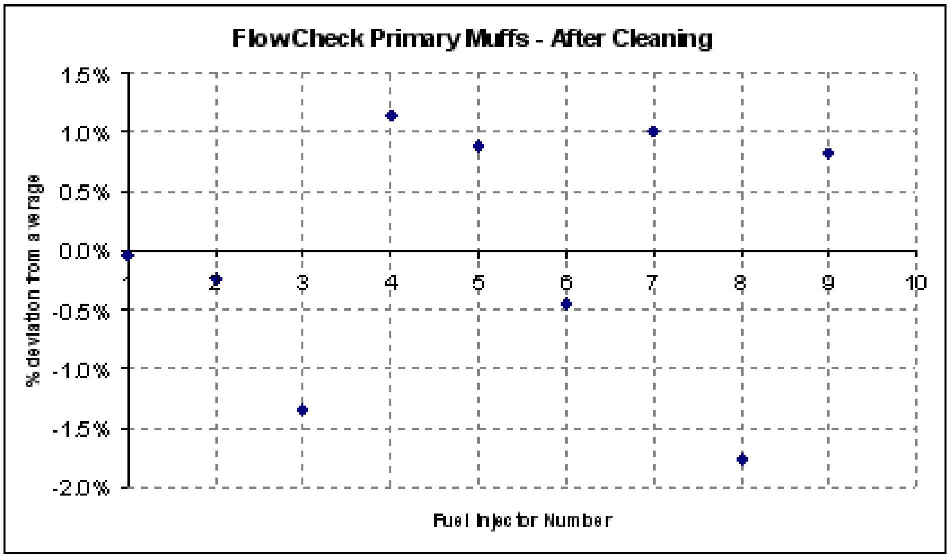



**Figure 1: Cold Flow Results For the Primary Fuel Muffs**

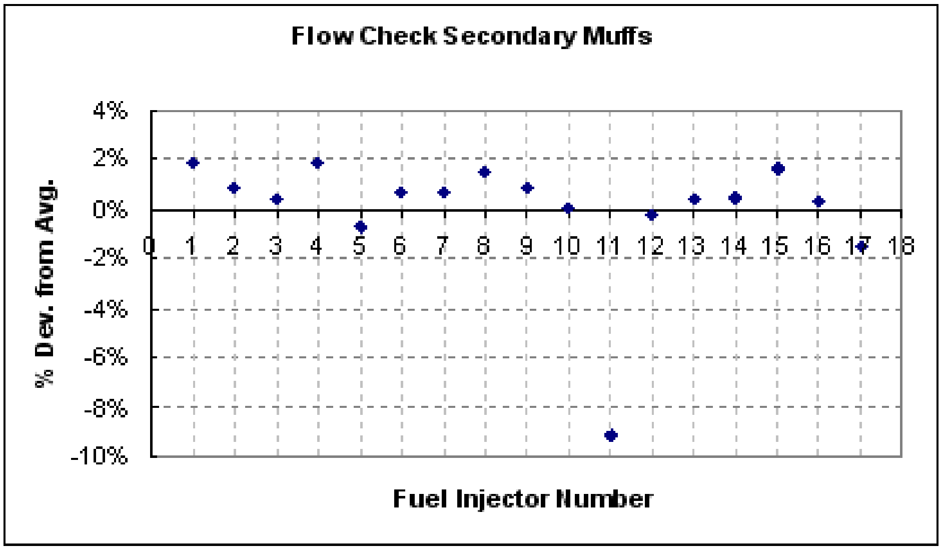



**Figure 2: Cold Flow Results For the Secondary Fuel Muffs**

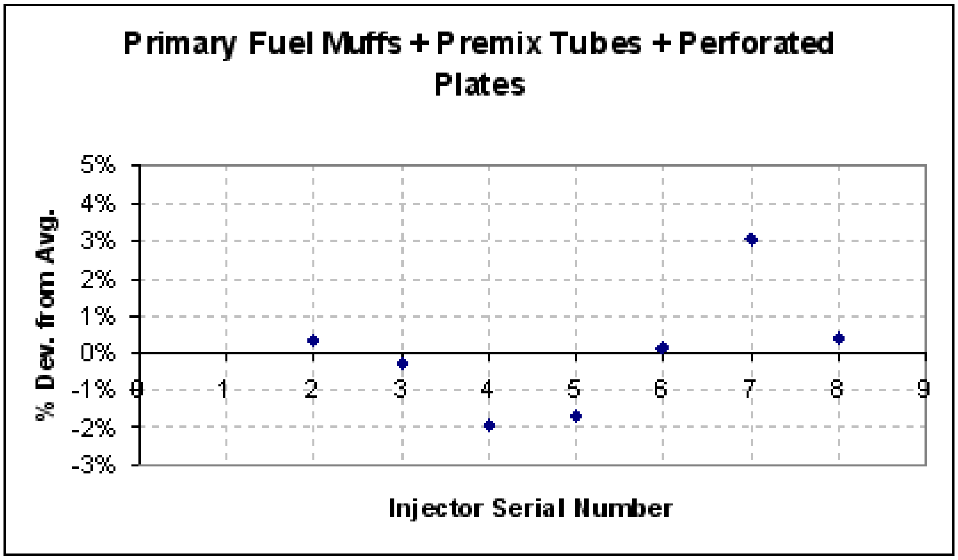



Figure 3: Cold Flow Results For the Primary Fuel Injector Complete Assemblies

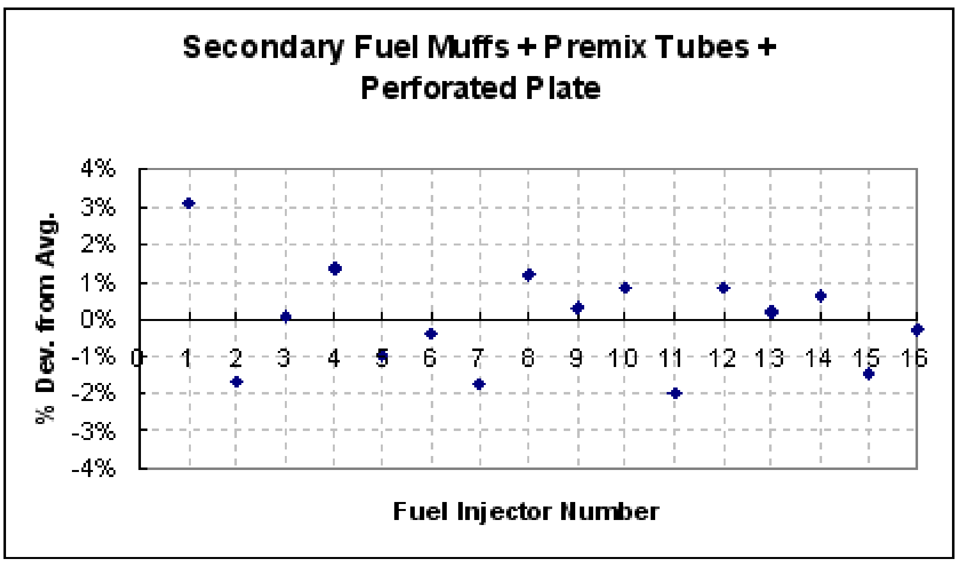



Figure 4: Cold Flow Results For the Secondary Fuel Injector Complete Assemblies

| Component | Effective Area (in^2) |
|---|---|
| Primary Stage Injectors (in^2) | 1.66 |
| Secondary Stage Injectors (in^2) | 6.72 |
| Liner (in^2) | 33.83 |
| Total | 42.21 |

**Table 1: Effective Areas of Various Components of the Preburner**

3.0.2 Premixer

The premixer has 24 fuel injectors located just upstream of the mixing vane assembly. These fuel injectors were flow tested individually to quantify part-to-part variation. This test was conducted at CESI's Mountain View facility. The data obtained from this test are plotted in Figure 5. It was found that all the injectors fall within acceptable range of -/+ 3 % deviation from the average.

Flow testing of the premixer air side was not conducted at this time as the premixer flow requirement was larger than the maximum flow capability of the test bench. Measurement of the flow/pressure drop characteristics of the complete premixer assembly will be conducted during premixer performance evaluation tests.

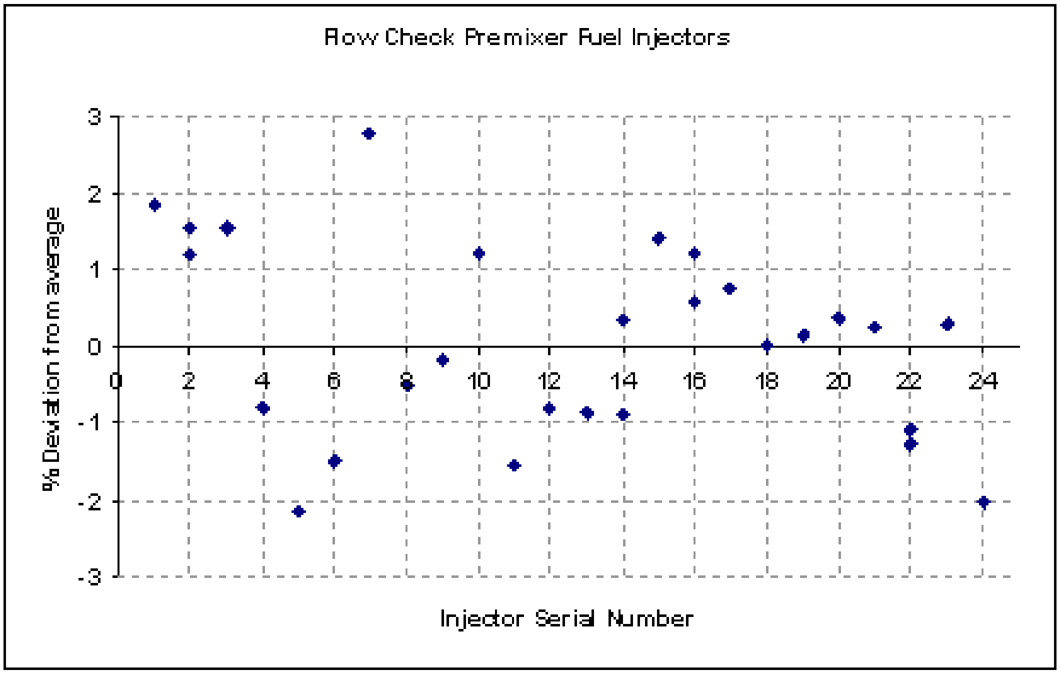



**Figure 5: Cold Flow Results For the Premixer Fuel Injectors**

### 3.0.3 Burnout Zone

The burnout zone liner (BOZ) has been designed with 100% backside cooling. Cooling air flows within an annulus formed between the BOZ liner and a larger diameter convector. In order to achieve the design pressure drop of approximately1.0 % and keep the wall temperature below 1650 $^0$F, cooling air is metered through a series of holes in the convector. The cold flow test indicated that total effective area of these holes was 36.35 in^2, which equates to a 1.16% pressure drop, acceptable for further testing.

## 4.0 Conclusions

The pressure drop component tests for the fuel injectors of the preburner and premixer show that the variation part-to-part is within acceptable limits of -/+ 3 %. The preburner testing indicated that it meets the design pressure drop requirement of 1.3 %. The premixer air side flow test could not be done due to a flow requirement beyond the capability of Solar's test facility. However, this test will be conducted as part of a premixer performance test. The BOZ pressure drop of 1.16%, although slightly high, meets the design intent for the rig testing. Overall all, the T70C combustion system components conform to design requirements.

## 8.4. Appendix I-D: Atmospheric Pressure Tests

## Appendix I-D: Atmospheric Pressure Testing

This appendix describes the test results of a series of full-scale combustor tests conducted at Solar Turbines. The preburner and premixer for the T-70 catalytic combustion system were tested at atmospheric pressure at simulated engine operating conditions. The preburner performance tests indicated that the primary stage had adequate turndown margin and the secondary stage had a wide operating range. The preburner exit temperature profiles were shown to be nearly flat for all conditions and $NO_x$ emissions were encouraging. The liner wall temperatures at design conditions were well within the 1650F requirement, and preburner pressure drop met the design criteria. The premixer met the required fuel-air and temperature uniformity at the catalyst inlet plane. The premixer pressure drop was well within the design requirements**.**

### Introduction

Atmospheric pressure tests of the catalytic combustor prototype components were conducted at Solar Turbines full-scale atmospheric test facility at Harbor Drive. The T-70C test rig was initially assembled with the preburner, non-active catalyst module, and the burnout zone. At the completion of the preburner performance tests, the premixer was installed to perform fuel-air uniformity tests. A description of the station numbers for various stages of the T-70 catalytic combustion system is given in Table 1.

### Objective

The main objective of this series of tests was to conduct the following characterization;

<u>Preburner</u>

- Primary stage performance
- Secondary stage performance
- Liner wall temperatures
- Emissions
- Exit temperature profile
- Pressure drop assessment

### Premixer

- Fuel-air uniformity at catalyst inlet plane
- Temperature uniformity at catalyst inlet plane
- Pressure drop

## Test Results

### Light off tests

The preburner light off performance was tested at various air inlet temperatures and flow rates. In general, the preburner showed good light off characteristics for primary zone equivalence ratio of as low as 0.4.

### Primary Stage Performance

The primary stage performance tests were conducted at conditions indicated in Table 2. These conditions cover the entire operating range of the engine from no load to full load for a wide range of ambient temperatures. These tests were conducted by fueling just the primary stage of the preburner. In each test, the primary stage equivalence ratio was slowly reduced until a flame out was achieved. The flame was observed through a quartz view port installed on the exhaust duct wall. A camera was used to display the image on a monitor inside the test cell. The results obtained from these tests are shown in Figures 1 through 4 for 600°, 700°, 800°, and 900 $^0$F inlet air temperatures, respectively. The figures show calculated primary zone adiabatic flame temperature plotted against preburner temperature rise. The results indicate that the primary stage has turndown capability to adiabatic flame temperatures of as low as 2000 $^0$F to 2200 $^0$F for varying inlet air temperatures and flow rates. This meets the preburner design requirements.

| **Station Description** | **Station number** |
|---|---|
| Compressor Discharge (rig inlet) | 2.20 |
| Preburner Inlet | 2.30 |
| Preburner Exit | 2.40 |
| Mixer | 2.50 |
| Catalyst Inlet | 2.60 |
| Catalyst Interstage | 2.65 |
| Catalyst Exit | 2.70 |
| BOZ Exit | 2.80 |

**Table 1: Station numbers for various stages of the combustion system**

| T2.3 ($^0$F) | Wa comb (pps) | T2.3 ($^0$F) | Wa comb (pps) | T2.3 ($^0$F) | Wa comb (pps) |
|---|---|---|---|---|---|
| 600 | 2.0 | 600 | 2.5 | 600 | 3.0 |
| 700 | 2.0 | 700 | 2.5 | 700 | 3.0 |
| 800 | 2.0 | 800 | 2.5 | 800 | 3.0 |
| 900 | 2.0 | 900 | 2.5 | 900 | 3.0 |

**Table 2: Preburner Atmospheric Pressure Test Conditions**

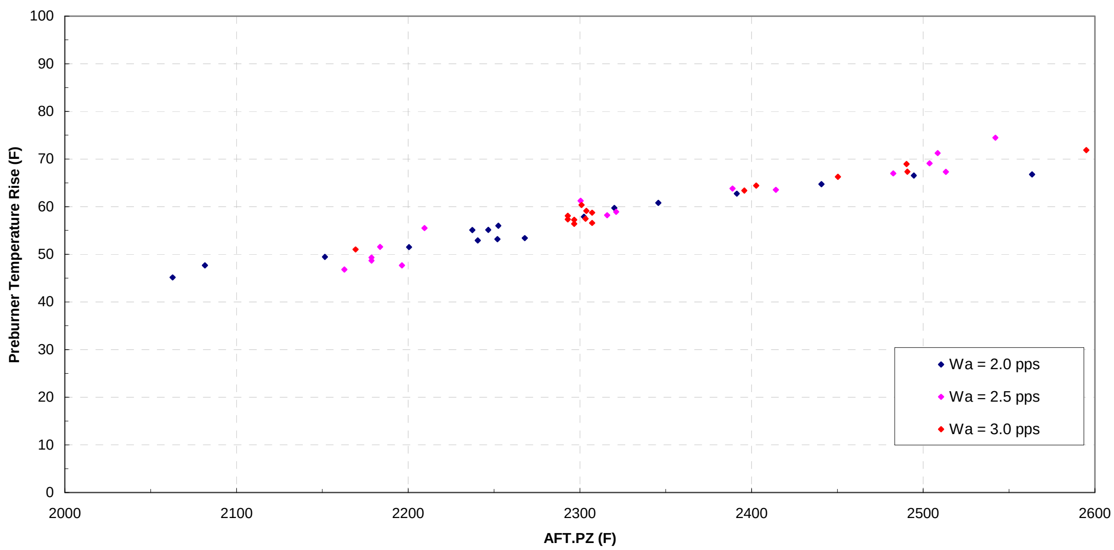



**Figure 1: Primary Stage Performance Test at Inlet Air Temperature of 600 $^0$F**

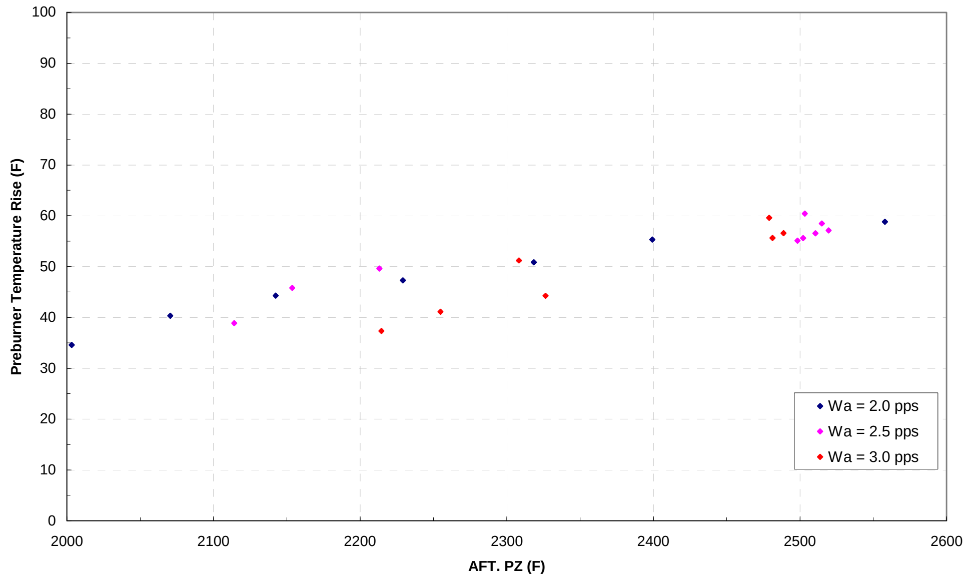



**Figure 2: Primary Stage Performance Test at Inlet Air Temperature of 700 $^{0}$F**

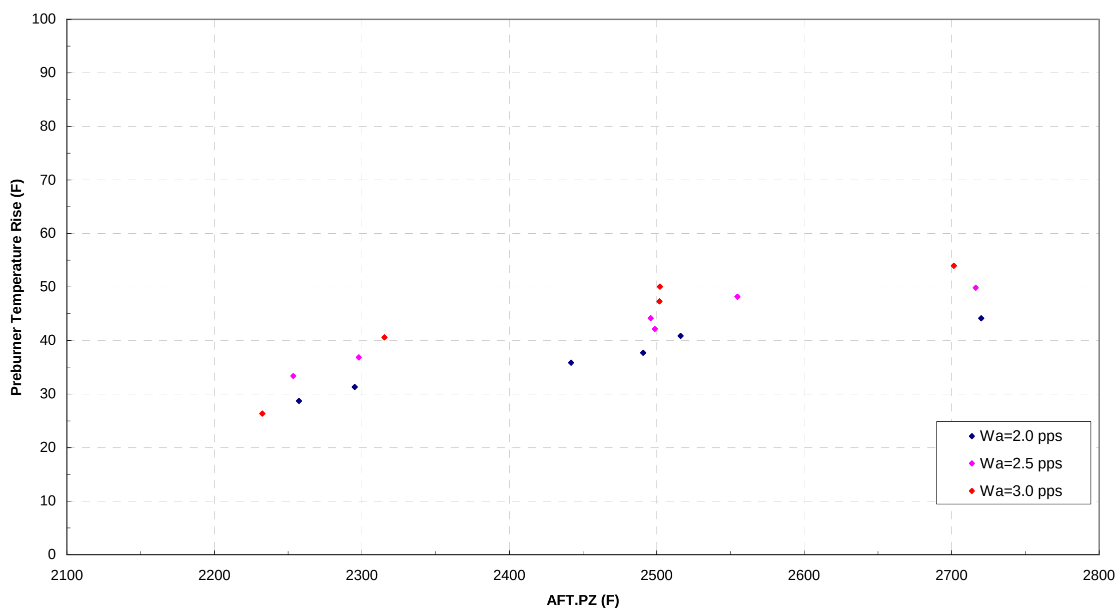



**Figure 3: Primary Stage Performance Test at Inlet Air Temperature of 800 $^{0}$F**

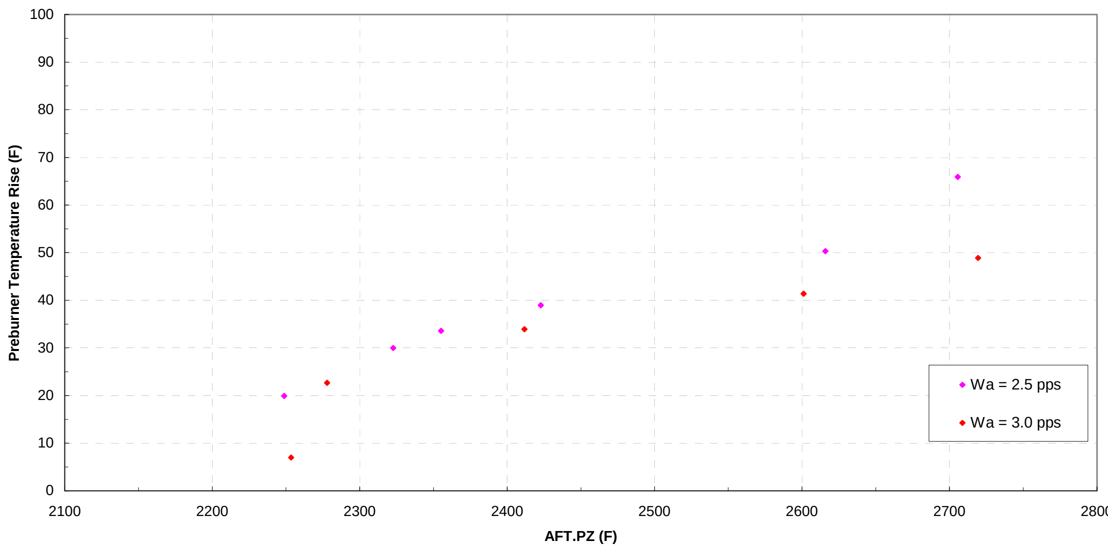



**Figure 4: Primary Stage Performance Test at Inlet Air Temperature of 900 $^{0}$F**

**Secondary Stage Performance**

Secondary stage performance tests were conducted at operating conditions shown in Table 2. At each operating condition, the primary stage equivalence ratio was set to a fixed value while the secondary zone equivalence ratio was varied. The results obtained from these tests are shown in Figures 5 through 8. The figures show secondary zone equivalence ratio plotted against preburner temperature rise for various operating conditions. The preburner total temperature rise was measured using three thermocouples at the preburner inlet and 32 thermocouples at the preburner exit. The results indicate that efficiency of the secondary zone is a strong function of primary stage equivalence ratio. At high primary zone equivalence ratios, the secondary zone starts to have fuel conversion at relatively leaner conditions. A sudden increase in the preburner temperature rise seems to occur between secondary zone equivalence ratio of 0.35 and 0.4 for all the operating conditions.

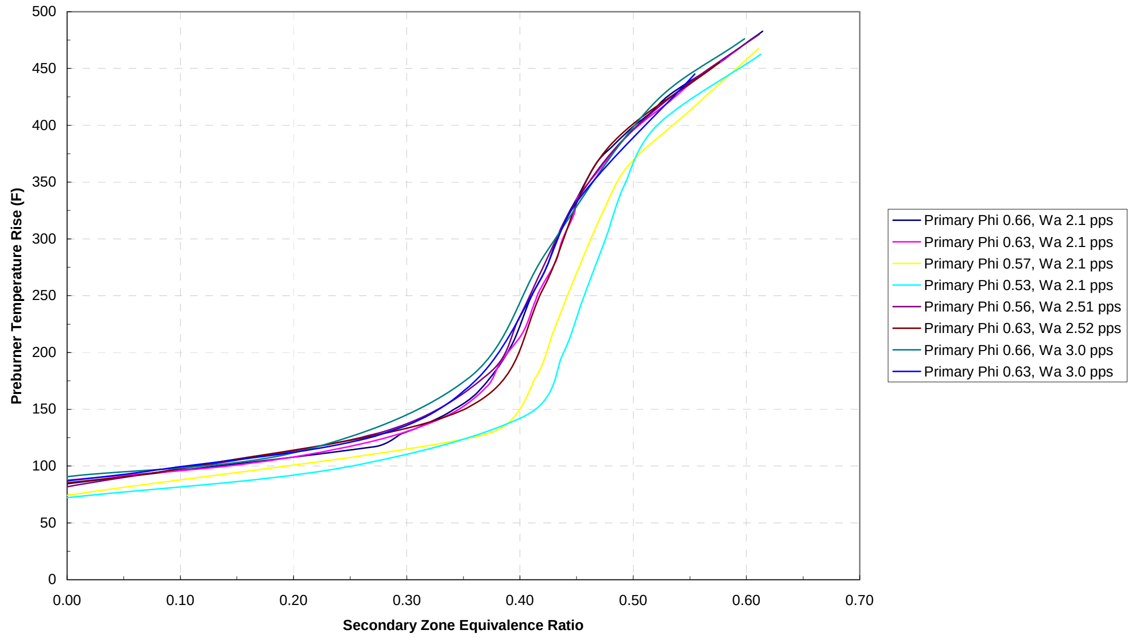



**Figure 5: Secondary Stage Performance Test at Inlet Temperature of 600 $^{0}$F**

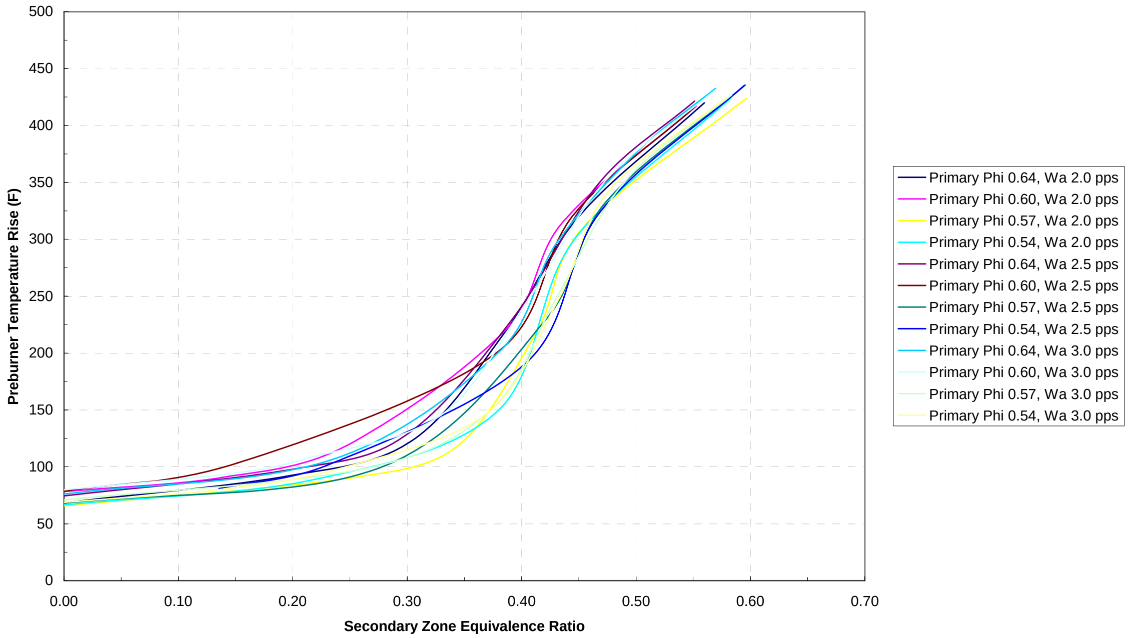



**Figure 6: Secondary Stage Performance Test at Inlet Temperature of 700 $^{0}$F**

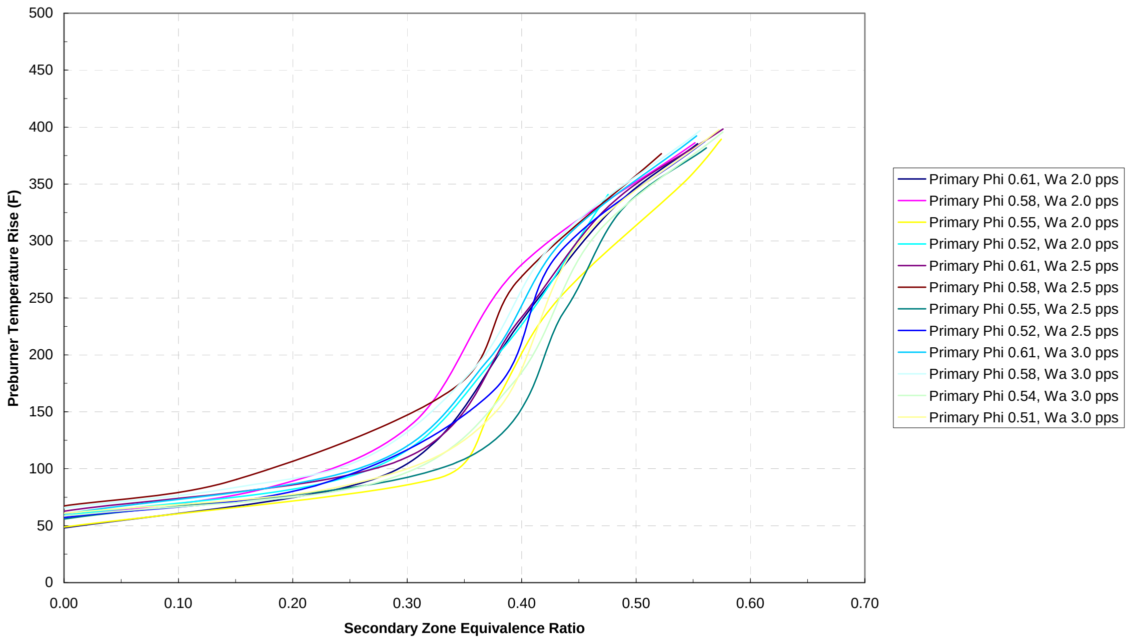



**Figure 7: Secondary Stage Performance Test at Inlet Temperature of 800 $^{0}$F**

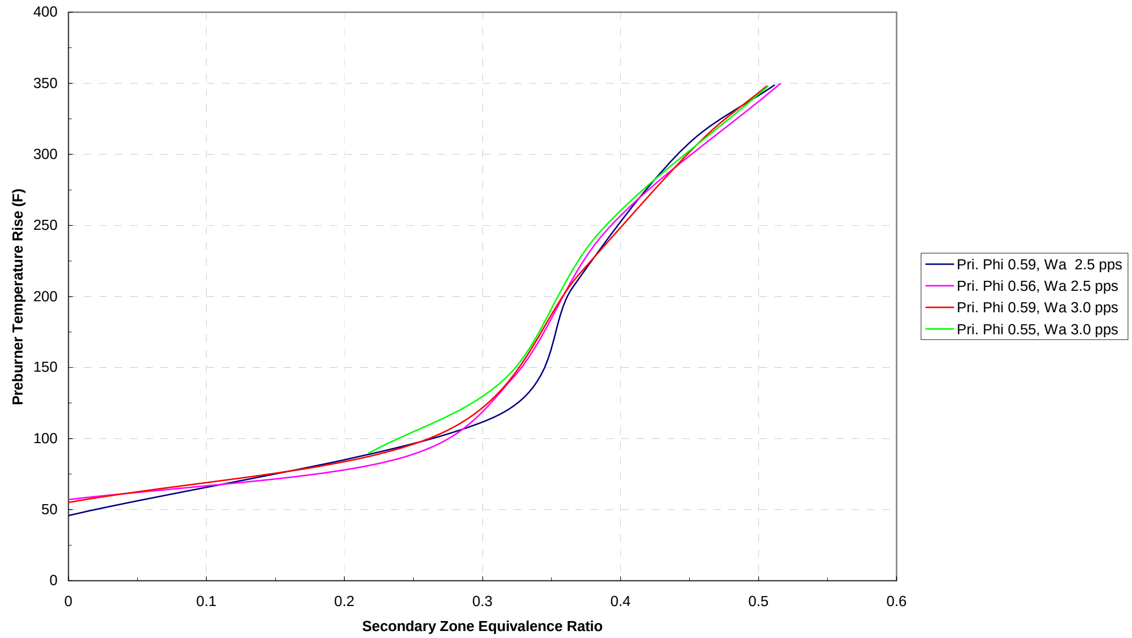



**Figure 8: Secondary Stage Performance Test at Inlet Temperature of 900 $^0$F**

### Preburner Liner Wall Temperatures

The outer and inner liners of the preburner were instrumented with type-K thermocouples to monitor wall temperatures. The liner wall temperatures were monitored for inlet air temperatures of 700°, 800°, and 900 $^0$ F. At each inlet air temperature, secondary zone equivalence ratio was varied while maintaining fixed air flow rate of 2.5 lb/sec. and primary zone adiabatic flame temperature of 2800 $^0$F. The inner and outer liner wall temperatures obtained from these tests are plotted in Figures 9 through 14 as a function of preburner temperature rise. In general, the outer liner wall temperatures showed a maximum of 1375 $^0$F, well within the design target of 1700 $^0$F. However, the inner liner wall temperatures reached close to 1700 $^0$F (TC locations 7 and 8) for a preburner temperature rise of close to 400 $^0$F. These two locations on the inner liner wall are directly opposite to the secondary jets where the secondary flames impinge at high preburner temperature rise. This operating condition corresponds to engine loads of less than 50 %. However, from 50 to 100 % load conditions, the inner liner wall temperatures show a maximum of 1400 $^0$F. As the preburner is expected to see minimal use at low loads, the current liner temperatures were deemed satisfactory for further rig testing.

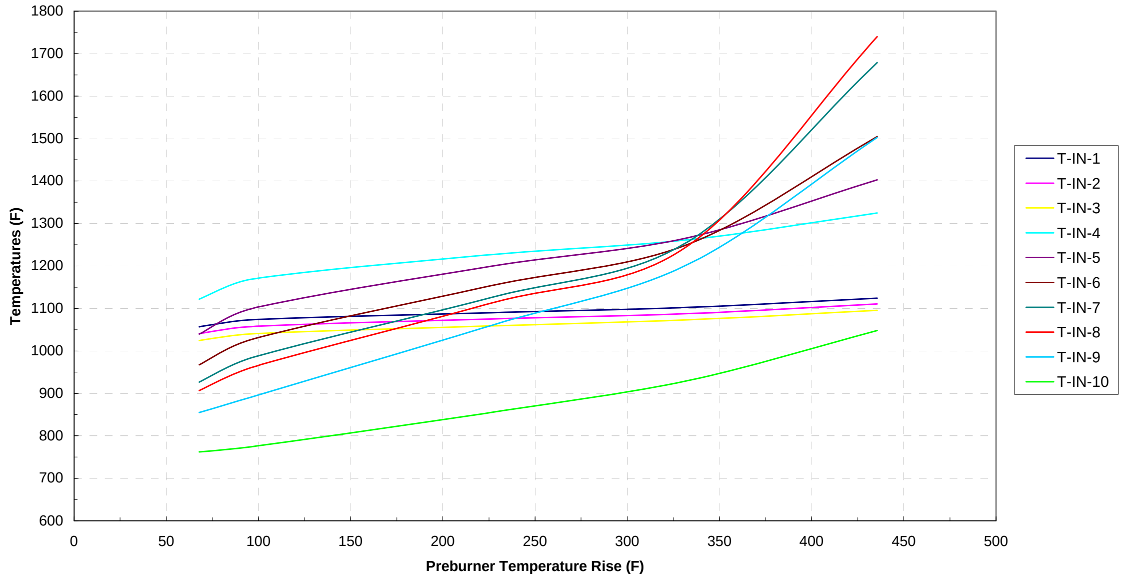



**Figure 9: Preburner Inner Liner Wall Temperatures at Inlet Air Temperature of 700 $^{0}$F**

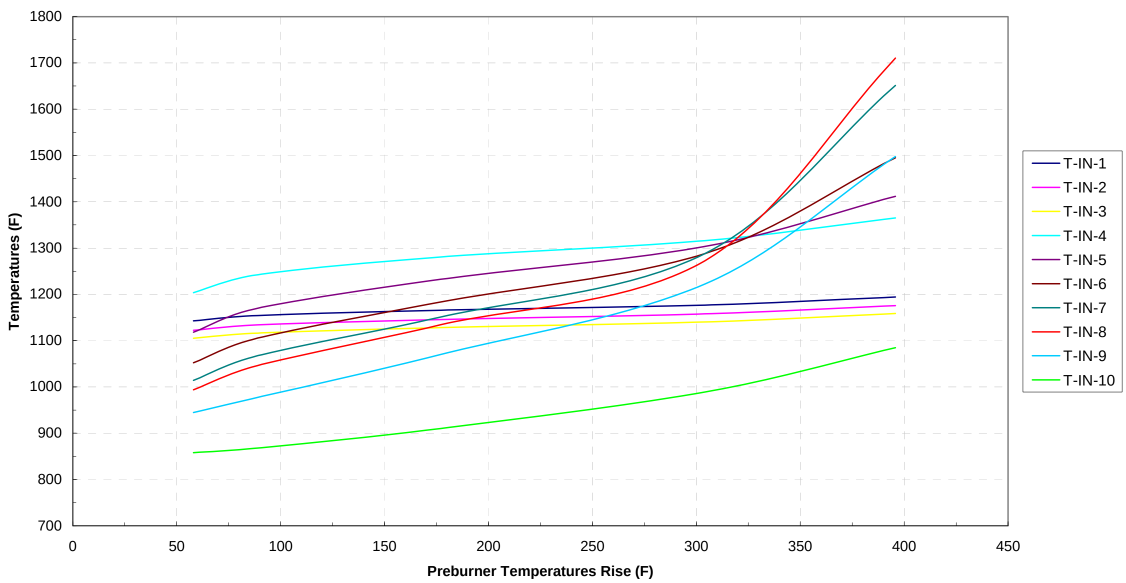



**Figure 10: Preburner Inner Liner Wall Temperatures at Inlet Air Temperature of 800 $^{0}$F**

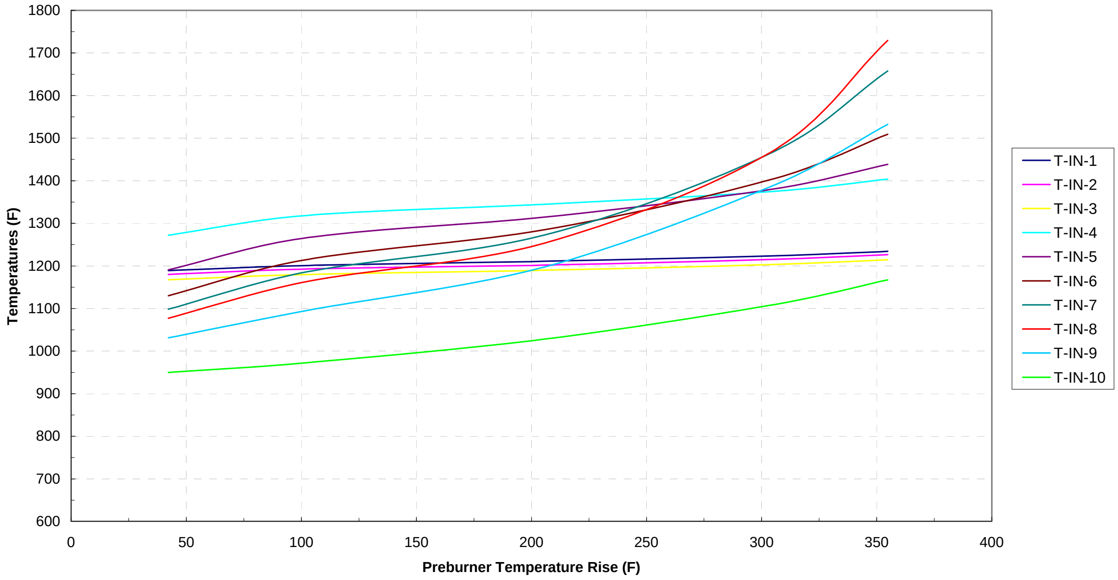



**Figure 11: Preburner Inner Liner Wall Temperatures at Inlet Air Temperature of 900 $^0$F**

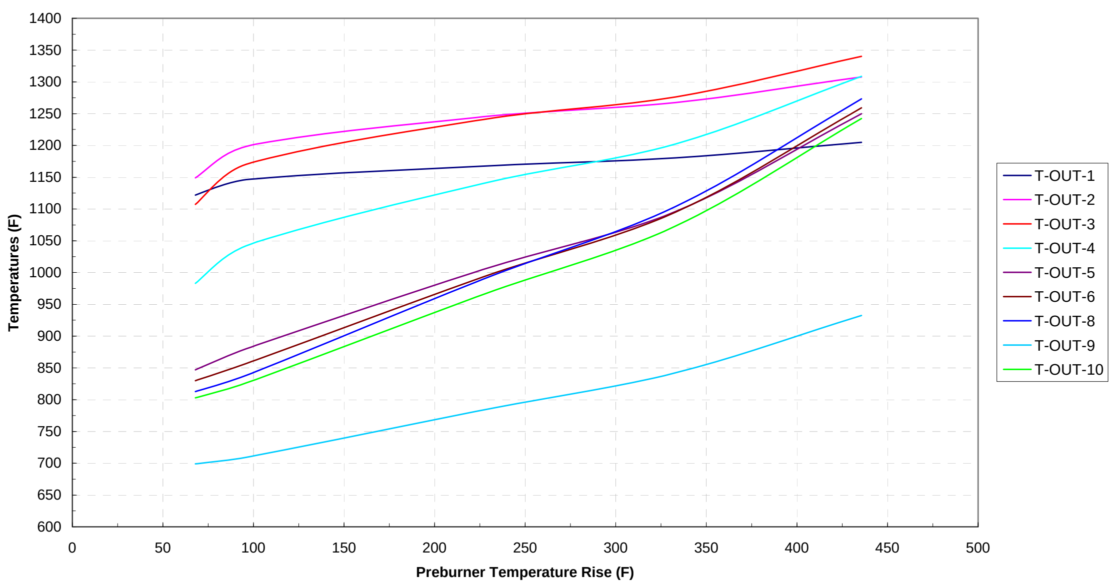



**Figure 12: Preburner Outer Liner Wall Temperatures at Inlet Air Temperature of 700 $^0$F**

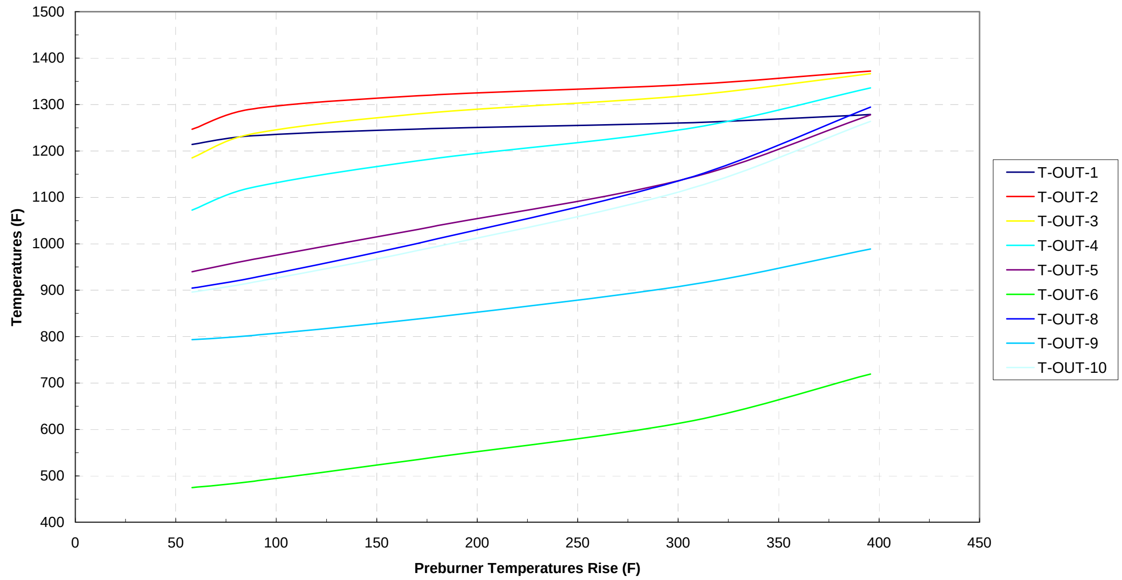



**Figure 13: Preburner Outer Liner Wall Temperatures at Inlet Air Temperature of 800 $^{0}$F**

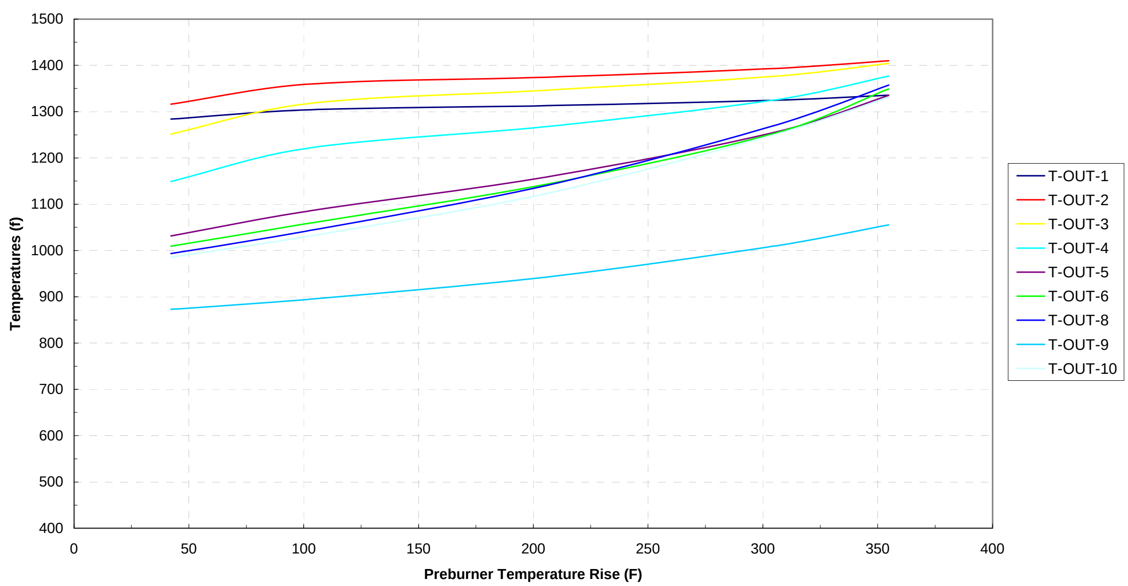



**Figure 14: Preburner Outer Liner Wall Temperatures at Inlet Air Temperature of 900 $^{0}$F**

**Preburner Emissions**
The preburner emissions test was conducted at several preburner inlet air temperatures and flow rates. The emissions rake located at the preburner exit consisted of four sampling tubes located 90 degrees apart and joined into a common manifold. Since the majority of the preburner $NO_x$ is created in the primary zone, secondary stage was not fueled in this test. The raw data obtained from this test has been corrected to account for dilution caused by turbine and scroll air-cooling and presented as turbine exhaust emissions (corrected to 15% $O_2$). Figure 15 shows corrected $NO_x$ emissions as a function of calculated flame temperature in the primary zone.

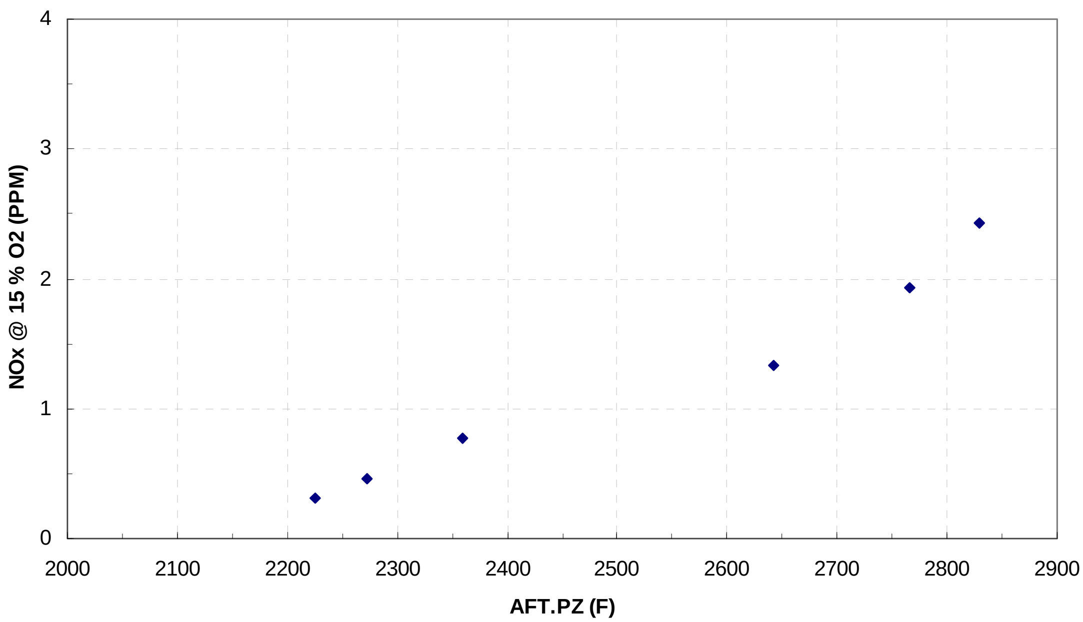



**Figure 15: Corrected Preburner Exit $NO_x$ Shown As Turbine Exhaust Emissions**

**Preburner Exit Temperature Profile**
This test was conducted using four rotating thermocouple rakes each containing 8 type-K thermocouples. The rake was rotated to collect data at each 1.875 degrees circumferential location around the preburner exit plane. The data were collected at simulated full speed no load and full speed full load conditions for a standard day operating condition. The results from these tests are shown in Figures 16 and 17. The preburner exit profile is very flat indicating minimum to maximum temperature difference of close to 70 $^0$F. This is excellent performance.

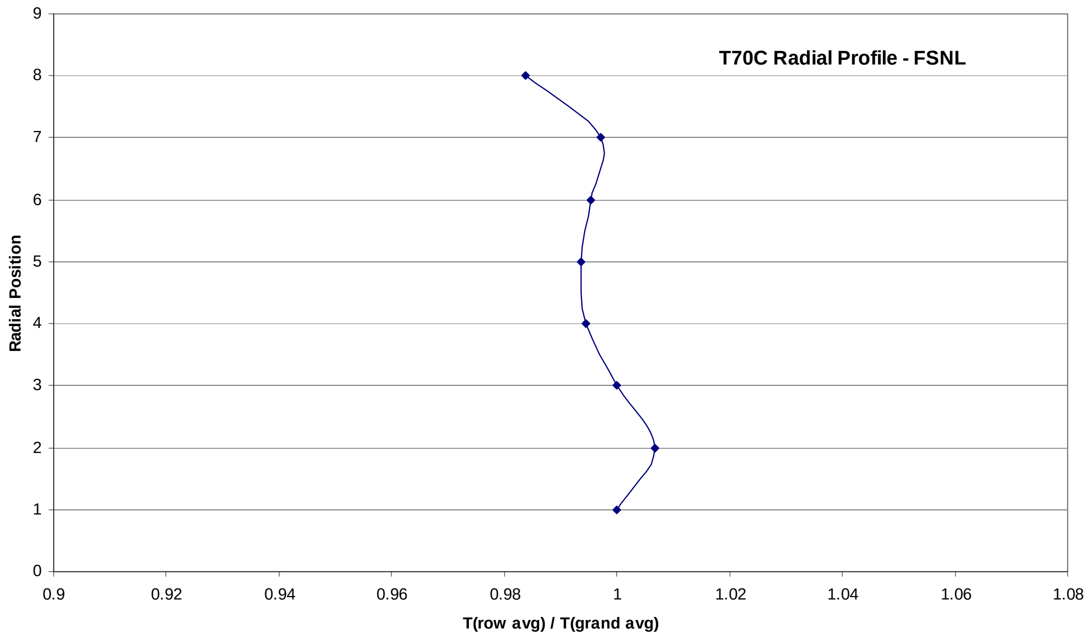



**Figure 16: Preburner Exit Temperature Profile at Simulated Full Speed No Load Condition**

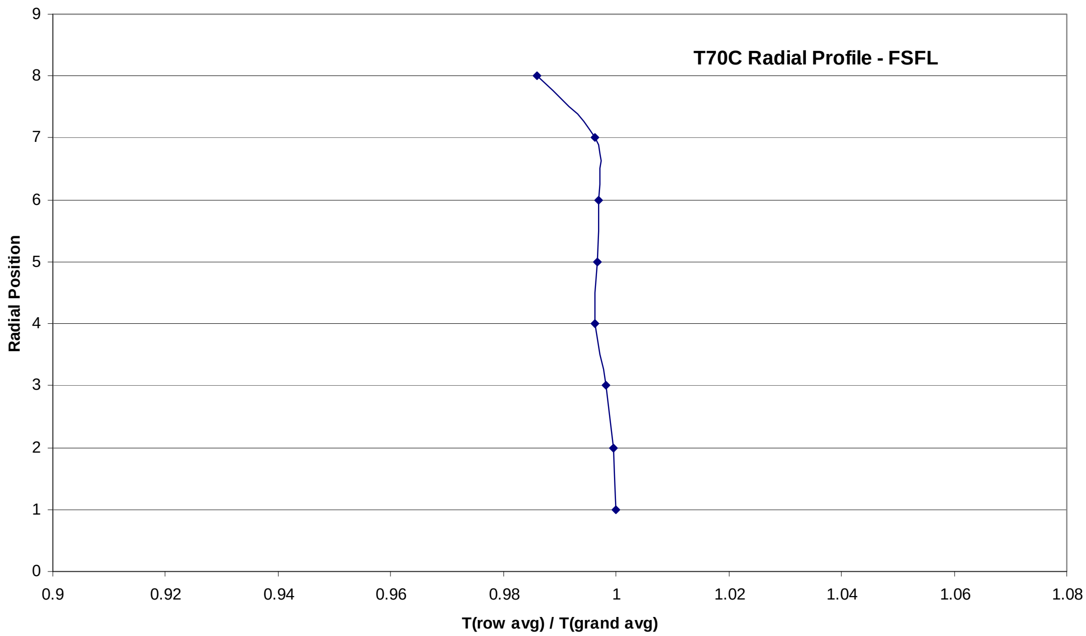



**Figure 17: Preburner Exit Temperature Profile at Simulated Full Speed Full Load Condition**

## Preburner Pressure Drop

The preburner design pressure drop was 1.3 % at full load on a standard day. The pressure drop was measured from inlet of the preburner to the exit. Figure 18 shows the overall pressure drop across preburner for various inlet air temperatures and flow rates. The design point is marked with a circle in the Figure 18 indicating that the preburner meets the design requirement for full load on a standard day operating condition.

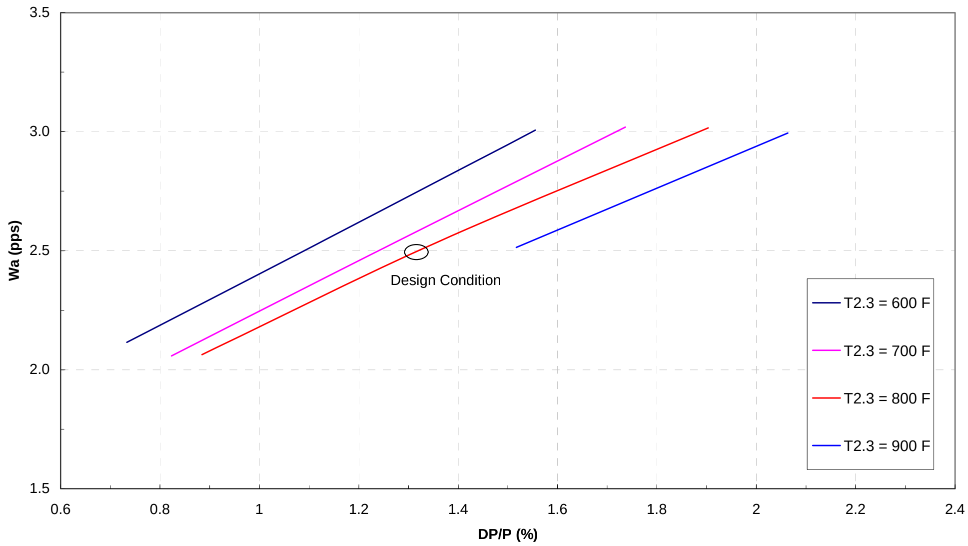



**Figure 18: Preburner Pressure Drop at Varying Inlet Air Temperatures and Flow Rates**

## Premixer Effectiveness

After completion of the preburner performance tests, the premixer was installed in the test rig downstream of the preburner. This test was conducted at simulated full load standard day operating condition shown in Table 3. The inlet face of the non-active catalyst module (having similar pressure drop as the active catalyst module) was instrumented with 24 sampling probes at various radial and circumferential locations on the reactor inlet face. Fuel-air samples were drawn individually from each of these sampling probes and sent to hydrocarbon analyzer for analysis. The results obtained from this test are plotted in Figure 19. It was noticed that majority of the data points fall with targeted -/+ 3% fuel-air uniformity except for three which fall within –6% uniformity. It was also noticed that the data points that fell outside the tolerance limit did not shown any specific trend. Premixing was deemed excellent and easily suitable for further system tests.

The premixer exit temperature uniformity was also measured using 12 thermocouples at the catalyst inlet plane. During this test, the preburner was operated at simulated full load condition on a standard day shown in Table 4. The results from this test are plotted in Figure 19, indicating that the difference between minimum and maximum temperature was 10 $^{0}$F. This is well within the design requirement of -/+ 59 $^{0}$F.

The premixer pressure drop was calculated from the difference of preburner exit and catalyst inlet static pressures. The result indicated that the pressure drop of 0.34 % was well within the design requirement of 0.47 %.

| Parameter | Condition |
|---|---|
| **Air Flow Rate (lb/sec.)** | **2.34** |
| **Fuel Flow Rate (lb/hr.)** | **202.2** |
| **Premixer Inlet Temperature ($^{0}$F)** | **931** |

**Table 3: Conditions For Premixer Fuel-Air Uniformity Test**

| Parameter | Condition |
|---|---|
| **Air Flow Rate (lb/sec.)** | **2.28** |
| **Primary Stage Fuel Flow (lb/hr.)** | **10.9** |
| **Secondary Stage Fuel Flow (lb/hr.)** | **19.9** |
| **Preburner Inlet Air Temperature ($^{0}$F)** | **800** |
| **Preburner Exit Temperature ($^{0}$F)** | **935** |

**Table 4: Conditions For Premixer Exit Temperature Uniformity Test**

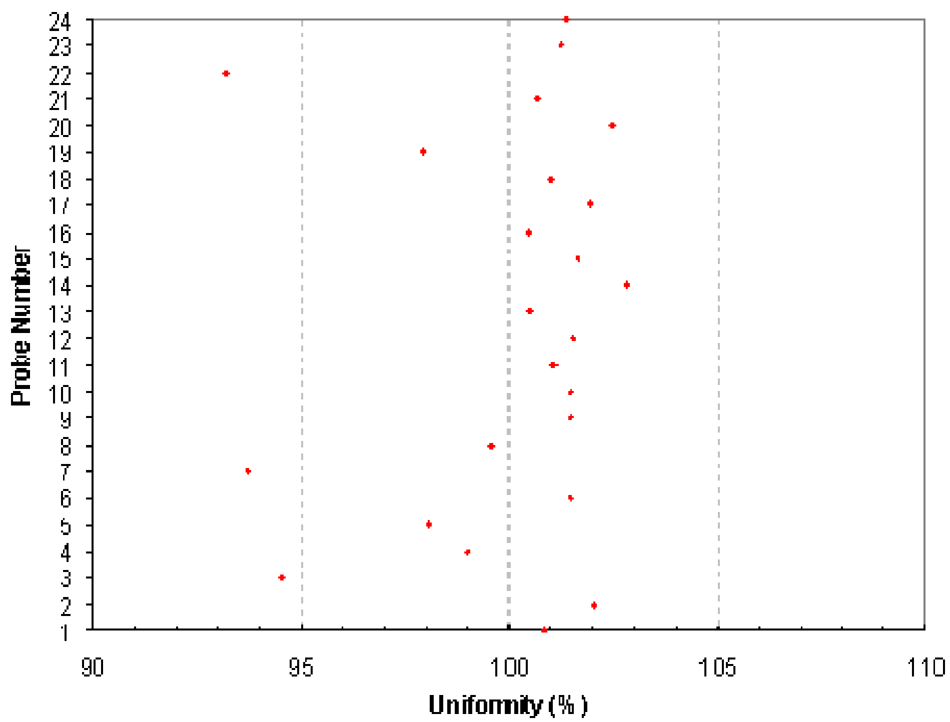



**Figure 19: Premixer Fuel-Air Uniformity Test at Simulated Condition**

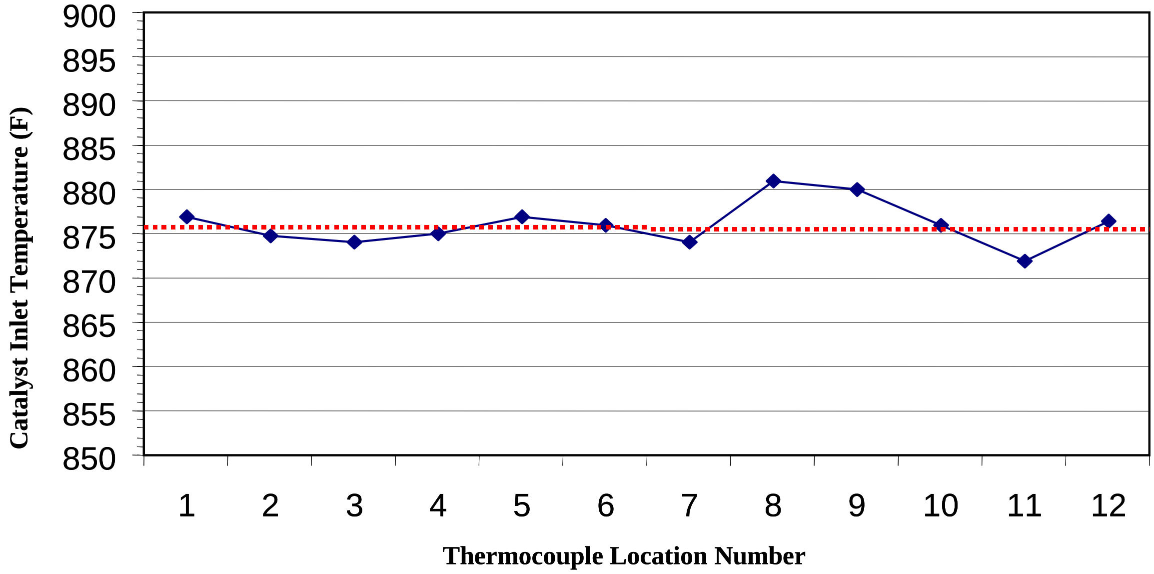



**Figure 20: Premixer Temperature Uniformity Test at Simulated Condition**

**Conclustions**

The following conclusions were drawn from the data analysis;

1. The preburner primary stage showed good light off and turndown characteristics for a wide range of inlet air temperatures and flow rates.
2. The preburner secondary stage showed smooth temperature rise curve for a wide range of equivalence ratios.
3. Combustion efficiency of the secondary stage is only a function of primary stage equivalence ratio.
4. The inner liner of the preburner shows a maximum temperature of 1700 $^0$F for a temperature rise of 400 $^0$F due to flame impingement from secondary injectors. This condition corresponds to less than 50 % load where engine is not expected to operate for extended periods of time.
5. The preburner exit $NO_x$ emissions meet the overall program goal of less than 2.5 ppm at the turbine exit
6. The preburner exit temperatures show an extremely flat profile for all simulated engine conditions
7. The overall pressure drop of the preburner meets the design goal.
8. The premixer meets the required fuel-air non-uniformity at the exit plane.
9. The premixer overall pressured drop meets the design requirements.
10. The premixer exit temperature profile meets the design goal.

Based on these tests, the preburner/ premixer performance was regarded as excellent. The hardware is easily suitable for high pressure testing of the reactive catalyst bed at the Caterpillar Technical Center.

## 8.5. Appendix I-E: Subscale Tests

# Appendix I-E: Catalytic Reactor Subscale Tests

**Overview**

This appendix presents the results of two evaluations conducted by CESI in support of California Energy Commission Contract 500-01-045.

The testing was conducted to verify the performance of the catalytic reactor on a reduced scale prior to fabrication of the full scale T-70 reactor module. The first evaluation focused on tests to substantiate the selection of the reactor foil configuration and the catalyst/washcoat specifications. The second test involved performance tests of a sub-scale reactor at simulated T-70 full and part-load conditions. Both series of tests were deemed successful and, subsequently, fabrication of the full scale catalytic module was started.

# Solar Turbines Taurus 70 Catalyst Production Qualification

## T-70 Module (S/N#AC001) Qualification

January 18, 2003

Executive summary

This report summarizes the qualifying results of the module production foils (module S/N#AC001) for the Solar Turbines Taurus 70 program. This module will be used in the Solar Turbines T-70 full-scale rig tests at the Caterpillar Test (CAT) Facility in Peoria, Illinois. Two catalyst foil samples from the production lot were tested. Test results from the qualification tests were within the desired performance specification.

Background

The Taurus 70 catalyst design program started in early 2002 and was completed in October, 2002. The module production foils were specified based upon results from this design program. Test pieces were taken from the production foil lots and set aside for the qualification tests. The test pieces were rolled into 2" diameter catalyst cores and installed into the rig at the CESI High Pressure Catalyst Test Facility. Two qualification test sequences were conducted. The Solar Turbines T-70 catalyst design is summarized as follows:

- Module inner, outer diameters: 1.3", 18.5"
- System: two catalyst stages
- 3" Inlet stage length
- 3" Outlet stage length

Test Description

The high pressure rig (HPR) located at CESI's Catalyst Test Facility in Mountain View, CA is used to test sub-scale (2.0" diameter) catalyst systems under simulated turbine conditions. The HPR is capable of operating at pressures from 1 to 28 atmospheres, and airflows up to 0.57 lbs/sec. The source air is heated to catalyst inlet temperatures via electric heaters and/or a diffusion flame natural gas preburner. Both the catalyst section and the post-catalyst burn-out zone (BOZ) sections of the HPR are insulated with an alumina fiber type insulation and water cooled. Pipeline natural gas (Pacific Gas & Electric Company) fuel is injected upstream of the catalyst and mixed to ±2% deviation from average fuel-to-air ratio. One or two water-cooled, single point emissions probes can sample from different axial locations in the BOZ. For the T-70 catalyst, a single probe was inserted into the BOZ at an axial distance equivalent to approximately 25-milliseconds downstream of the catalyst outlet. Downstream of the BOZ, the combustion air is cooled then exhausted to the atmosphere through a back-pressure regulated control valve.

Before catalyst performance testing starts, the catalyst system is operated at steady-state conditions for approximately 12 hours. During this process, the catalyst inlet gas temperature and fuel flow through the catalyst are set to achieve a defined catalyst operating temperature. This test is conducted to minimize changes in catalyst performance during subsequent tests.

The standard catalyst system performance test is a ‘preheat step-up’ test with constant $T_{ad}$ (adiabatic combustion temperature). This starts at a low catalyst inlet temperature where the homogeneous combustion (HC) front is located near the exit of the BOZ and full burnout (CO, UHC’s <10ppm) may not be established at the probe position. The catalyst inlet temperature is then increased in discrete steps. During each step, the fuel flow is lowered to keep the measured $T_{ad}$ constant. This process increases the catalyst operating temperature which causes the HC front to move closer to the catalyst. The step-up process is continued until a pre-defined maximum catalyst operating temperature or the rig’s preheat temperature limit is reached.

**Table 1** summarizes the tests run on the two T-70 qualification foils and lists the figures and tables within this report where those tests are detailed. Two samples were tested, each at two different conditions:

- T-70 Base load, scaled: pressure and flow scaled down from the T-70 base load condition due to the limitations of the CAT test facility in Peoria, Il.
- T-70 Base load, engine: engine conditions at ISO ambient.

**Table 1.** CESI Sub-Scale Test Summary.

| Date Conducted | Foil Sample | Test Type | Target Condition |
|---|---|---|---|
| 12/18/2002 – 12/19/2002 (overnight) | A | Steady-state | T-70 Base load, scaled |
| 12/19/2002 | A | Tph Step-up | T-70 Base load, scaled |
| 12/19/2002 | A | Tph Step-up | T-70 Base load, engine |
| 12/19/2002 – 12/20/2002 (overnight) | B | Steady-state | T-70 Base load, scaled |
| 12/20/2002 | B | Tph Step-up | T-70 Base load, scaled |
| 12/20/2002 | B | Tph Step-up | T-70 Base load, engine |

Results

The T-70 catalyst is designed to obtain the target operating temperature when the inlet gas temperature is 932°F (± 25°F) while at base load (engine or scaled) conditions. **Figure 1** shows the catalyst operating temperature as a function of the inlet gas temperature. The design target was met for both qualification tests at the full-pressure T-70 base load point as well as the equivalent lower pressure scaled condition.

The design target for pressure drop across the catalyst is 1.0% dP/CDP with a maximum pressure drop limit of 1.2% dP/CDP. **Table 2** lists the pressure drop results during the T-70 qualification tests. All pressure drop results met the design target.

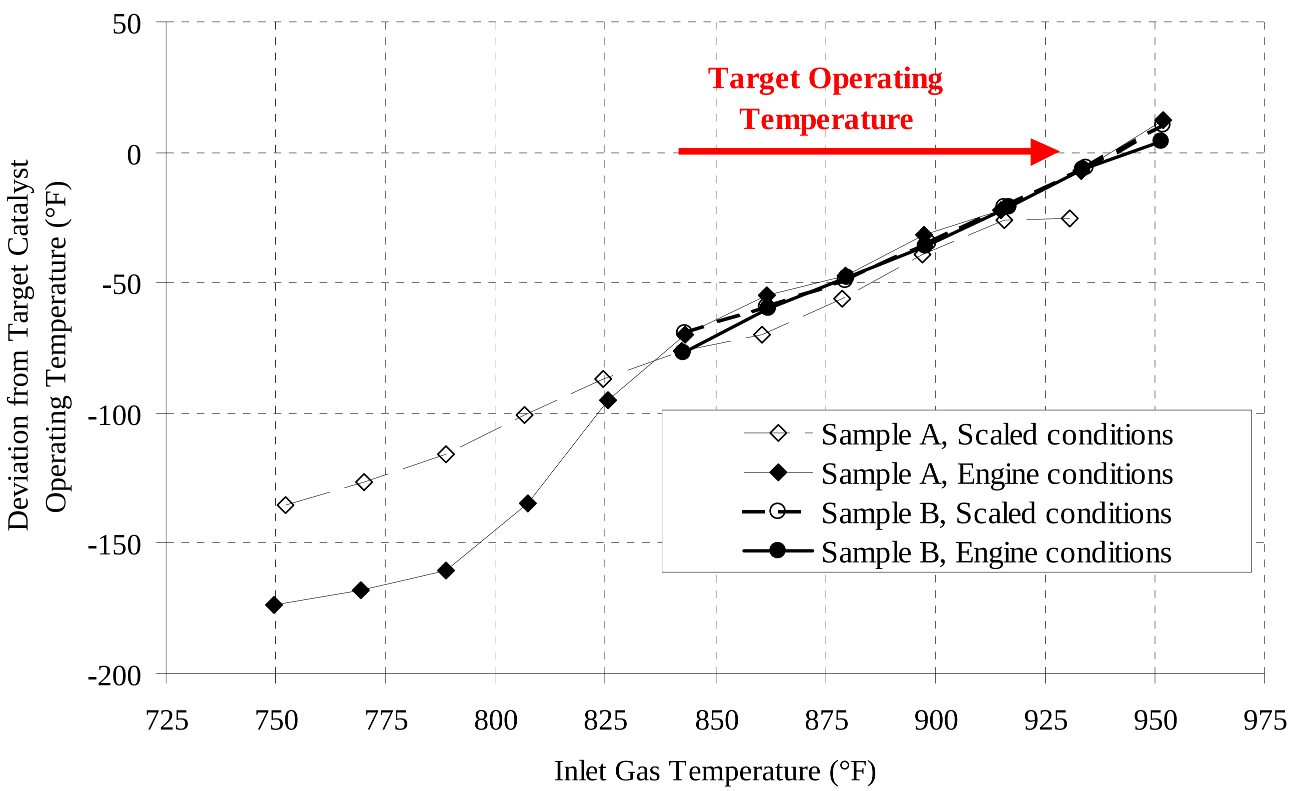



**Figure 1.** Sub-scale test results, T-70 catalyst system temperature (catalyst inlet gas temperature vs. catalyst operating temperature while at base load conditions).

**Table 2.** Sub-scale test results, T-70 catalyst system pressure drop at base load conditions, catalyst inlet gas temperature equals 932°F.

| **Description:** Load Pt, Foil Sample | Target (variability) (%dP of CDP) | Measured Value (%dP of CDP) |
|---|---|---|
| Base load, Sample A | 1.0 (±0.2) | 0.8 |
| Base load, Sample B | 1.0 (±0.2) | 0.9 |
| Base load, Scaled, Sample A | 1.0 (±0.2) | 0.9 |
| Base load, Scaled, Sample B | 1.0 (±0.2) | 1.0 |

Conclusions

The catalyst foils used for the T-70 full-scale module production (S/N# AC001) met all performance requirements at the two conditions tested. Based upon these results, the module was accepted for commercial release.

Solar Turbines Taurus 70 Catalytic Reactor Test

## Sub-Scale Reactor Test at
## T-70C Full and Part Load Conditions

October 21, 2003


### *Executive summary*

This report summarizes sub-scale catalyst test results at scaled T-70 engine operating conditions identical to the planned full-scale rig tests at the Caterpillar Test (CAT) Facility in Peoria, Illinois. Catalyst performance and burnout zone (BOZ) emissions data were collected at the 5%, 25%, 50% and full load T-70 operating conditions. Low emissions (CO, UHC < 10 ppm) were obtained over the desired emissions range (50% to full load).


### Background

The catalyst performance tests described in this report were conducted during July of 2003 and are in addition to the production qualification that was summarized in an earlier report (January 18, 2003). Catalyst foils used were from the same production batch (S/N # AC001) as during the qualification.

### Test Description

The high pressure rig (HPR) located at CESI's Catalyst Test Facility in Mountain View, CA is used to test sub-scale (2.0" diameter) catalyst systems under simulated turbine conditions. The HPR is capable of operating at pressures from 1 to 28 atmospheres and air flow up to 0.57 lbs/sec. The source air is heated to catalyst inlet temperatures with electric heaters and/or a diffusion flame natural gas preburner. Both the catalyst section and the post-catalyst BOZ of the

HPR are insulated with an alumina fiber insulation and water-cooled. Pipeline natural gas (Pacific Gas & Electric Company) is injected upstream of the catalyst and mixed to ±2% of the average fuel-to-air ratio. Water-cooled, single point emissions probes can sample from different axial locations in the BOZ. For the T-70 catalyst, a single probe was inserted into the BOZ at an axial distance equivalent to approximately 25-milliseconds residence time downstream of the catalyst outlet. Downstream of the BOZ, the combustion gases are cooled and then exhausted through a back-pressure control valve.

Before the catalyst performance tests, the catalyst system was operated at steady-state conditions for approximately 4 hours. During this process, the catalyst inlet gas temperature and fuel flow through the catalyst were set to achieve a defined catalyst operating temperature.

The catalyst performance tests were designed to simulate, as close as possible, the expected test conditions during the full-scale test conditions at the CAT facility. These tests were catalyst fuel flow "step-up" tests with the catalyst inlet gas temperature held constant. Tests start at a low fuel/air ratio where the homogeneous combustion (HC) front is located near the exit of the BOZ and full burnout (CO, UHC's < 10ppm) may not be established at the probe position. The catalyst fuel flow is then increased in discrete steps. Thus, the measured adiabatic combustion temperature ($T_{ad}$) increases between each step. This process increases the catalyst operating temperature which causes the HC front to move closer to the catalyst. The step-up process is continued until a pre-defined maximum catalyst operating temperature or the maximum design $T_{ad}$ is obtained.

Table AA-1 (see Appendix AA) details the operating conditions during each test. Note that multiple tests were conducted at the 100% and 50% load conditions. Tests were conducted to obtain catalyst performance data at several different inlet gas temperatures. Note that all conditions were scaled down in pressure and flow from the actual T-70 engine conditions in order to simulate the anticipated full-scale operating conditions at the CAT facility. This is required because full load T-70 combustion airflow is approximately 39 lb/sec while the CAT facility is limited to 28 lb/sec. Scaling was done to maintain the same gas velocities in the test rig as in the T-70C combustor.

## Results

Tests at the scaled full load condition indicate that the catalyst / BOZ system can obtain full burn-out (UHC, CO <10 ppm) under a wide range of combustion temperatures (2240°F to 2550°F) at several different catalyst inlet temperatures (835°F, 925°F, and 1014°F). See Table AA-2 for the detailed temperature, emissions and flow data for all full load test points.

Figure 1 shows the catalyst operating temperature as a function of the adiabatic combustion temperature, as measured by thermocouples located within the BOZ. Each line shown on the graph is a catalyst operating line at a constant inlet temperature (and varying fuel / air ratio). The test data indicate that to operate the reactor at full load conditions, a catalyst inlet temperature of approximately 900°F will be required. At these conditions CO and reactor-generated $NO_x$ will be very low. The low emissions operating range of the catalyst under full load conditions extends approximately 80°F below the target catalyst operating temperature before CO emissions start to increase.

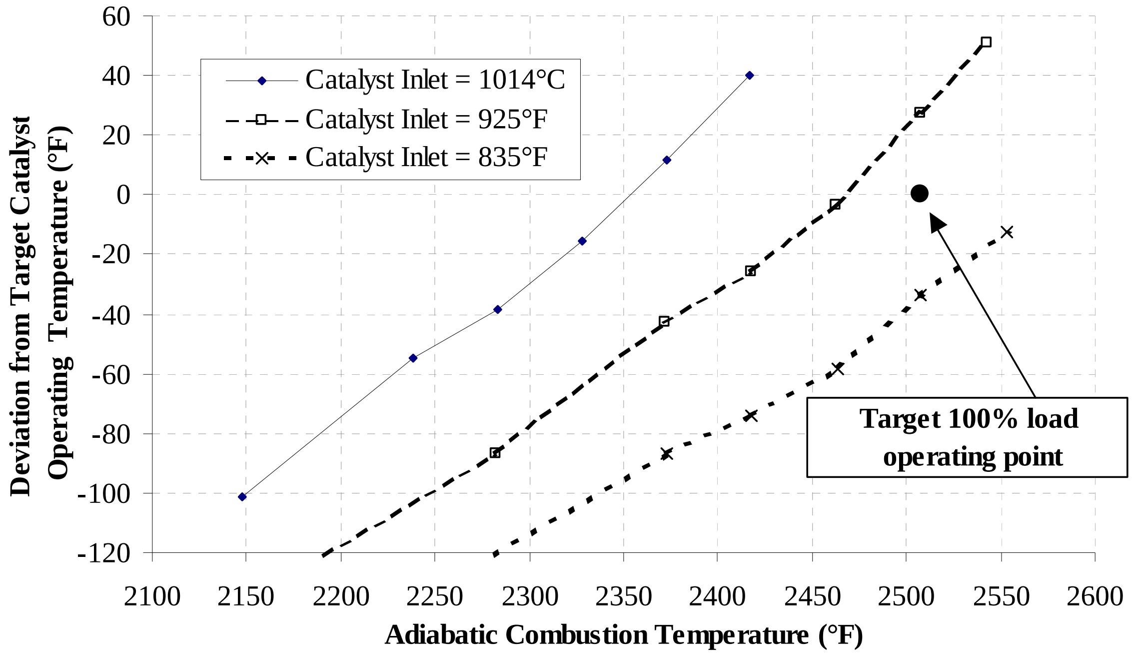



Figure 1. Subscale Test Results (Scaled to Full Load Conditions)

System $NO_x$ emissions are not reported in this document. Prior experience has established that the $NO_x$ emissions from the T-70C (Xonon combustion system) will be determined by the $NO_x$ formed in the preburner. Since the preburner design used in the subscale HPR rig is substantially different from the full-scale T-70C combustor (diffusion flame vs. lean pre-mixed), the $NO_x$ measured in the rig is not representative of the full-scale combustor.

Figure 2 and Table AA-3 give the catalyst / BOZ performance data at the T-70 50% load condition. A reactor inlet temperature of approximately 840°F will be required to meet the 50% load point. Similar to full load, full burn out is obtained over a wide range of inlet gas and BOZ combustion temperatures. The low emissions operating range of the catalyst at 50% load extends approximately 40°F below the target catalyst operating temperature before CO emissions start to increase. As expected, turndown of the reactor is more restricted at part load engine operating conditions.

Figure 3 and Table AA-4 give the catalyst / BOZ performance data at the T-70 25% load condition and a reactor inlet temperature of 1157°F. Full burn out was not obtained over the reactor temperature range tested. At the highest reactor temperature (2193°F), hydrocarbon levels were below 10 ppm but CO was at 19 ppm. This suggests that preburner temperatures may have to be too high (excessive $NO_x$) to achieve acceptable CO emissions. This inability to provide low emissions at low engine load is typical of lean combustion systems and an expected result.

Figure 3 and Table AA-5 give the catalyst / BOZ performance data at the T-70 5% load condition. Similar to the 25% condition, full burn out is not attained. Low emissions are not expected from the T-70 at this low load.

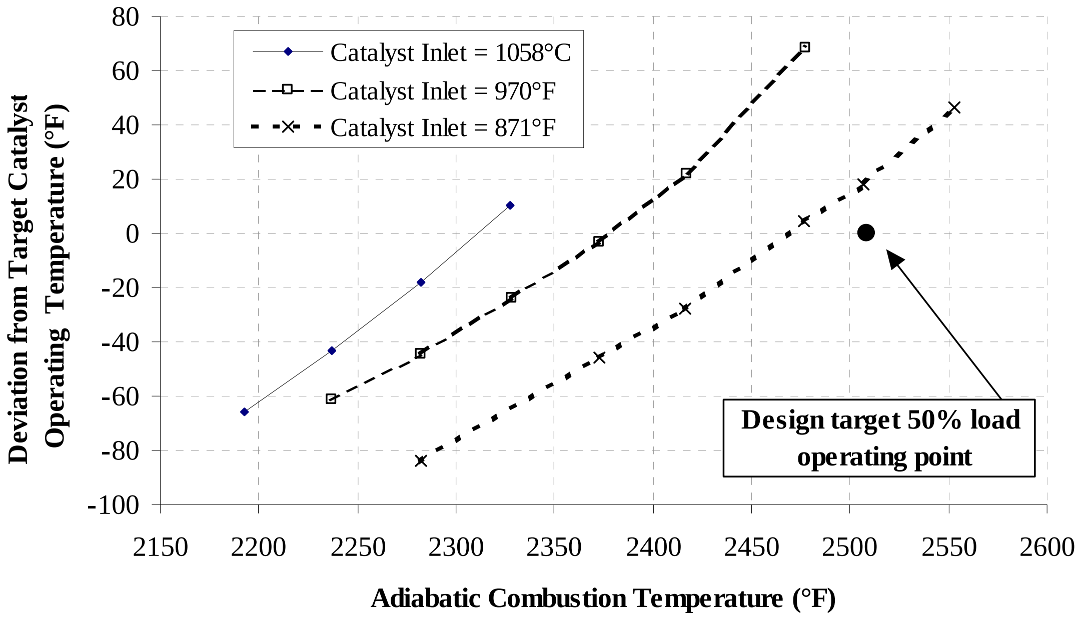



Figure 2. Scaled T-70, 50% load sub-scale test results, adiabatic combustion temperature vs. catalyst operating temperature.

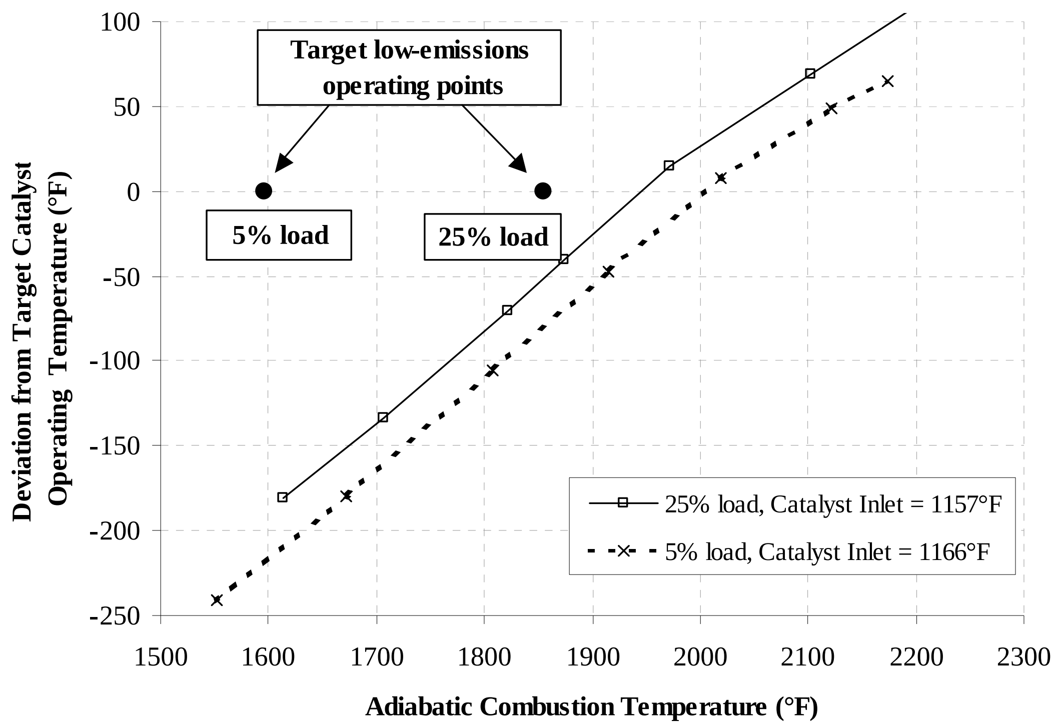



Figure 3. Scaled T-70, 25% and 5% load sub-scale test results, adiabatic combustion temperature vs. catalyst operating temperature.

## Conclusions

The T-70 catalyst was tested at several simulated load points over a wide range of catalyst inlet and adiabatic combustion temperatures (BOZ outlet). Catalyst performance was determined by measured catalyst operating temperatures, BOZ combustion temperatures, and BOZ emissions (CO and UHC). Full burn out (CO and UHC < 10 ppm) was obtained at both the 50% load and full load conditions. UHC and CO emissions at the 5% and 25% load points were above 10 ppm. $NO_x$ was not used as a measure of reactor performance as $NO_x$ emissions in the Xonon system are generated in the premixer. The subscale reactor testing indicates that low emissions should be achieved with the full scale catalyst over a range of 50 to 100% load, a range that is in line with expectations.

## Appendix AA

Table AA-1. Performance Test Conditions.

| T-70 load pt | Inlet Pressure (psig) | Airflow (slpm)* | Preburner temperature rise (°F) | Catalyst Inlet Gas Temp (°F) |
|---|---|---|---|---|
| Full load | 162 | 7030 | 460 | 1014 |
| Full load | 162 | 7030 | 460 | 925 |
| Full load | 162 | 7030 | 460 | 835 |
| 50 % load | 140 | 6285 | 435 | 1058 |
| 50 % load | 140 | 6285 | 435 | 969 |
| 50 % load | 140 | 6285 | 435 | 870 |
| 25 % load | 131 | 7030 | 580 | 1157 |
| 5 % load | 123 | 7030 | 625 | 1166 |

* Standard liters per minute.

Table AA-2. Catalyst and BOZ Performance at Scaled Full Load
(Preburner temperature rise = 460°F)

| **Catalyst Inlet Conditions** | | | | **Catalyst** | **BOZ *** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Gas Temperature** | **Airflow** | **Fuel Flow** | **Press.** | **Pressure drop** | **Gas Temperature** | **$O_2$** | **UHC** | **$CO_2$** | **CO** |
| **°F** | **Slpm** | **slpm** | **Psig** | **psid** | **°F** | **vol%** | **ppm** | **vol%** | **ppm** |
| 1013 | 7030 | 197.2 | 161.8 | 1.63 | 2148 | 13.90 | 131 | 3.76 | 632 |
| 1014 | 7032 | 214.9 | 161.9 | 1.68 | 2238 | 13.47 | 1.6 | 4.12 | 6.8 |
| 1014 | 7028 | 224.3 | 161.7 | 1.70 | 2283 | 13.50 | 1.3 | 4.33 | 2.5 |
| 1014 | 7028 | 233.4 | 161.9 | 1.72 | 2328 | 13.26 | 1.1 | 4.47 | 2.6 |
| 1014 | 7043 | 243.2 | 161.7 | 1.75 | 2373 | 13.01 | 1.0 | 4.63 | 3.0 |
| 1014 | 7035 | 252.5 | 161.8 | 1.77 | 2417 | 12.74 | 1.0 | 4.77 | 3.2 |
| 925 | 7043 | 221.9 | 161.8 | 1.59 | 2192 | 12.98 | 201 | 4.26 | 665 |
| 926 | 7023 | 239.6 | 161.5 | 1.62 | 2282 | 12.77 | 7.7 | 4.73 | 7.2 |
| 926 | 7005 | 257.9 | 162.1 | 1.66 | 2372 | 12.27 | 0.6 | 5.05 | 0.0 |
| 925 | 7032 | 268.8 | 161.4 | 1.70 | 2418 | 12.02 | 0.6 | 5.19 | 0.0 |
| 926 | 7040 | 278.3 | 161.7 | 1.71 | 2462 | 11.76 | 0.4 | 5.34 | 0.0 |
| 925 | 7026 | 287.1 | 162.1 | 1.72 | 2507 | 11.46 | 0.5 | 5.50 | 0.0 |
| 926 | 7026 | 295.8 | 161.6 | 1.76 | 2543 | 11.25 | 0.5 | 5.62 | 0.4 |
| 835 | 7045 | 257.8 | 161.4 | 1.57 | 2282 | 12.51 | 334 | 4.86 | 615 |
| 835 | 7039 | 274.2 | 161.5 | 1.60 | 2373 | 11.90 | 6.3 | 5.26 | 14 |
| 835 | 7041 | 286.1 | 161.4 | 1.63 | 2418 | 11.61 | 1.0 | 5.42 | 0.3 |
| 835 | 7052 | 296.0 | 161.6 | 1.65 | 2463 | 11.33 | 0.6 | 5.57 | 0.0 |
| 835 | 7044 | 305.0 | 161.8 | 1.66 | 2507 | 11.05 | 0.5 | 5.72 | 0.2 |
| 836 | 7021 | 314.4 | 161.9 | 1.68 | 2554 | 10.76 | 0.9 | 5.87 | 0.5 |

* BOZ emissions taken 20.5” downstream of the catalyst outlet.

Table AA-3. Catalyst and BOZ Performance at 50% Load
(Preburner temperature rise = 435°F )

| Catalyst Inlet Conditions | | | | Catalyst | BOZ * | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Gas Temperature** | **Airflow** | **Fuel Flow** | **Press.** | **Pressure drop** | **Gas Temperature** | **$O_2$** | **UHC** | **$CO_2$** | **CO** |
| **°F** | **slpm** | **slpm** | **psig** | **Psid** | **°F** | **vol%** | **ppm** | **vol%** | **ppm** |
| 1058 | 6285 | 180.9 | 140.4 | 1.62 | 2192 | 13.69 | 16 | 4.00 | 81 |
| 1058 | 6285 | 189.9 | 140.3 | 1.65 | 2237 | 13.55 | 0.8 | 4.16 | 6.2 |
| 1059 | 6271 | 196.6 | 140.4 | 1.66 | 2282 | 13.51 | 0.4 | 4.35 | 0.0 |
| 1059 | 6269 | 204.1 | 140.5 | 1.68 | 2327 | 13.27 | 0.4 | 4.49 | 0.0 |
| 969 | 6268 | 202.3 | 140.6 | 1.56 | 2237 | 13.40 | 107 | 4.40 | 314 |
| 970 | 6267 | 209.1 | 140.5 | 1.58 | 2282 | 13.10 | 3.8 | 4.59 | 16 |
| 969 | 6274 | 219.4 | 140.3 | 1.61 | 2328 | 12.83 | 0.6 | 4.74 | 0.0 |
| 969 | 6263 | 226.8 | 140.3 | 1.63 | 2373 | 12.57 | 0.3 | 4.87 | 0.0 |
| 970 | 6271 | 234.8 | 140.8 | 1.64 | 2417 | 12.32 | 0.3 | 5.02 | 0.0 |
| 970 | 6266 | 246.5 | 140.4 | 1.69 | 2478 | 11.96 | 0.3 | 5.22 | 0.0 |
| 870 | 6269 | 221.6 | 140.8 | 1.50 | 2282 | 12.37 | 66 | 4.71 | 140 |
| 870 | 6270 | 239.4 | 140.4 | 1.55 | 2373 | 11.97 | 2.6 | 5.10 | 7.1 |
| 872 | 6276 | 248.9 | 140.5 | 1.58 | 2417 | 11.84 | 0.8 | 5.29 | 2.2 |
| 872 | 6272 | 260.2 | 140.6 | 1.61 | 2477 | 11.48 | 0.7 | 5.49 | 1.9 |
| 872 | 6262 | 265.7 | 140.7 | 1.61 | 2507 | 11.30 | 0.6 | 5.59 | 1.6 |
| 872 | 6273 | 275.3 | 140.3 | 1.64 | 2553 | 11.02 | 0.5 | 5.73 | 1.8 |

* BOZ emissions taken 20.5” downstream of the catalyst outlet.

Table AA-4. Catalyst and BOZ Performance at 25% Load
(Preburner temperature rise = 580°F)

| **Catalyst Inlet Conditions** | | | | **Catalyst** | **BOZ *** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Gas Temperature** | **Airflow** | **Fuel Flow** | **Press.** | **Pressure drop** | **Gas Temperature** | **$O_2$** | **UHC** | **$CO_2$** | **CO** |
| **°F** | **slpm** | **slpm** | **Psig** | **Psid** | **°F** | **vol%** | **ppm** | **vol%** | **ppm** |
| 1156 | 7032 | 77.8 | 131.2 | 1.84 | **1614**** | 17.78 | 5626 | 1.75 | 531 |
| 1156 | 7044 | 94.5 | 131.3 | 1.88 | **1707**** | 17.48 | 6225 | 1.86 | 998 |
| 1157 | 7034 | 115.9 | 131.3 | 1.95 | **1822**** | 16.96 | 6108 | 2.03 | >1000 |
| 1157 | 7024 | 125.8 | 131.4 | 1.97 | **1874**** | 16.61 | 5392 | 2.13 | >1000 |
| 1157 | 7034 | 145.2 | 131.5 | 2.03 | **1972**** | 15.41 | 1584 | 2.67 | >1000 |
| 1158 | 7041 | 157.6 | 131.7 | 2.09 | 2103 | 14.24 | 48 | 3.80 | 542 |
| 1158 | 7032 | 174.0 | 131.3 | 2.16 | 2193 | 13.74 | 3.9 | 4.10 | 19.2 |

* BOZ emissions taken 20.5” downstream of the catalyst outlet.
** Incomplete combustion in the BOZ. $T_{ad}$ gas temperature calculated via catalyst inlet temperature and methane concentration.

Table AA-5. Catalyst and BOZ Performance at 5% Load
(Preburner temperature rise = 625°F)

| **Catalyst Inlet Conditions** | | | | **Catalyst** | **BOZ *** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Gas Temperature** | **Airflow** | **Fuel Flow** | **Press.** | **Pressure drop** | **Gas Temperature** | **$O_2$** | **UHC** | **$CO_2$** | **CO** |
| **°F** | **slpm** | **slpm** | **Psig** | **psid** | **°F** | **vol%** | **ppm** | **vol%** | **ppm** |
| 1166 | 7035 | 67.5 | 122.6 | 1.99 | **1552**** | 18.14 | 5236 | 1.78 | 306 |
| 1166 | 7034 | 88.5 | 122.6 | 2.06 | **1672**** | 17.79 | 6256 | 1.92 | 580 |
| 1166 | 7032 | 113.9 | 122.6 | 2.14 | **1808**** | 17.26 | 6747 | 2.11 | >1000 |
| 1167 | 7029 | 134.7 | 122.5 | 2.21 | **1914**** | 16.66 | 6063 | 2.29 | >1000 |
| 1167 | 7034 | 155.7 | 122.5 | 2.27 | **2018**** | 15.36 | 1952 | 2.86 | >1000 |
| 1167 | 7031 | 175.5 | 122.6 | 2.32 | 2121 | 14.21 | 169 | 3.93 | 943 |
| 1167 | 7038 | 186.3 | 122.6 | 2.36 | 2174 | 13.85 | 32 | 4.17 | 260 |

* BOZ emissions taken from sample probe located 20.5” downstream of the catalyst outlet.
** Incomplete combustion in the BOZ.

## 8.6. Appendix I-F: High Pressure Tests

## Appendix I-F: Steady State Test Report

This appendix describes the tests of the T-70 catalytic combustion system conducted at the CTC. Testing occurred in a combustion test rig with high pressure and high air flow capability.

### 1. Summary

The prototype Taurus 70 (T-70) catalytic combustion system was tested in a rig at the Caterpillar Technical Center (CTC) in Peoria. The CTC facility, although larger than the facilities at Solar Turbines, is not able to match all of the operating conditions of a T-70 engine. Therefore, the tests were run at reduced pressure. Airflow was reduced in proportion to the pressure to maintain combustor gas velocities at engine design levels. Table 1 summarizes full load, T-70 operating conditions (sea level and at 59 F ambient temperature) as well as the maximum facility capabilities.

**Table 1: Combustion System Test Conditions**

| | Taurus 70 Engine (nominal design conditions) | Maximum Test Facility Capabilities | Rig Conditions for Combustor Testing | Preburner Test Conditions |
|---|---|---|---|---|
| T2 ($^0$F) | 800 | >800 | 600 | 600, 750, 804, 850 |
| P2 (psia) | 250 | 175 | 150 | 155, 175 |
| Wa (pps) | 39.1 | 27 | 24.8 | 24.8, 25.8 |
| BOZ ($^0$F) | 2500 | n.a | 2200 | - |
| PBDT ($^0$F) | 186 | n.a. | 440 | 70-450 |

* T2 and P2 are combustor inlet temperature and pressure
* Wa is combustor inlet air flow rate
* BOZ is burnout zone
* PBDT is preburner temperature rise

Testing was conducted in two phases. Initial testing focused only on the preburner and the premixer (no catalytic reactor fueling). Subsequently, the entire combustion system was tested. The complete system included the preburner, premixer, catalytic reactor and burnout zone (BOZ).

The preburner tests were run over the range of conditions shown in Table 1 (column 5). Performance was excellent. The test data indicated good turndown margin both for the primary and the secondary preburner stages covering 0-100 % load conditions. The preburner pressure drop and $NO_x$ emissions were well within design requirements. The CO emissions were higher than 10 ppm since the BOZ design goal of 2500 $^0$F could not reached due to rig limitations. The preburner testing covered a wide range of burner inlet temperatures to simulate operation over a range of ambient temperatures.

Preburner performance is critical to the overall combustion system performance as the majority of the $NO_x$ formed in the combustion system originates in the preburner. Very little $NO_x$ is formed in the catalytic reactor itself. The CTC tests demonstrated that preburner performance at high-pressure was essentially unchanged from earlier atmospheric pressure tests.

Testing of the fuel/air premixer focused on demonstrating the high level of mixing required at the upstream face of the catalytic reactor. The test results indicated fuel/ air uniformity at the catalyst inlet was within the targeted -/+ 5 percent range. A comparison of the premixer performance at both atmospheric and high-pressure test conditions showed that performance was independent of operating pressure.

The full catalytic combustion system was tested at the conditions shown in Table 1 (column 4). The results showed emissions of 1.7 ppm $NO_x$ (15 % $O_2$), which is consistent with the assumption that the majority of $NO_x$ is formed in the preburner. The overall system pressure drop was less than 3.5 %, thus meeting the design requirement.

As actual engine conditions cannot be achieved in a rig at Solar Turbines or CTC, the next step in the combustion system assessment is an on-engine test.

## 2. Results

The purpose of the high-pressure tests was to document, to the extent possible in a rig, the performance of the T-70 catalytic combustion system. The full scale, prototype hardware was tested at simulated engine conditions at the CTC in Peoria. The initial tests were conducted on the preburner and the premixer. Subsequent tests involved the entire system including the catalyst module and burnout zone (BOZ). The tests were conducted in accordance with previously published test plans by Solar Turbines and CESI (see Refs., Section 4). The instrumentation locations for the complete combustion system are shown in Fig. 1.

### 2.1 Preburner Performance Tests

**Light off tests**

The light-off tests were conducted at varying preburner inlet conditions (temperatures, pressures, and air flow rates). The results indicated that the preburner had good light off characteristics for primary zone equivalence ratios of 0.6 and higher for a wide range of inlet conditions.

**Primary Stage Performance**

The primary stage performance was tested at conditions shown in Table 2. These rig inlet conditions simulated a T-70 operating range from 50 to 100% load. At each operating condition, the primary stage fuel flow was slowly reduced until a lean blow out was achieved. The results from these tests are shown in Fig. 2 where primary zone equivalence ratio has been plotted against preburner temperature rise. The preburner temperature rise was calculated from thermocouples at the preburner inlet and premixer inlet. The primary stage showed good lean stability, down to equivalence ratios of 0.45 to 0.47 for all the operating conditions tested. Figure 3 shows same data plotted against the calculated primary zone flame temperature.

**Secondary Stage Performance**

Once the primary stage turndown capability was established, the secondary stage efficiency tests were conducted at conditions shown in Table 2 for varying primary zone equivalence ratios. At each condition, the primary zone equivalence ratio was fixed at 10 percent higher than the lean blow out equivalence ratio. The secondary zone equivalence ratio was then increased in increments. The data thus obtained are plotted as a function of the preburner temperature rise in Fig. 4. The secondary zone showed good turndown capability as indicated by a temperature rise even at very low secondary zone equivalence ratios. A good turndown capability of the secondary stage ensures smooth engine control at part load operation.

**Preburner Liner Wall Temperatures**

The preburner wall temperatures were measured at all the operating conditions indicated in Table 2. The results were similar at all test conditions, and typical data are shown in Figs. 5 and 6. The wall temperature data are plotted against preburner temperature rise in Figs. 5 and 6 for the inner and outer liners, respectively. The maximum liner wall temperatures fell well below the target temperature of 1600 $^{0}$F throughout the preburner operating range, which suggests good preburner durability.

**Preburner Emissions**

The preburner emissions were measured at all the operating conditions, and test data are plotted in Figs. 7, 8, and 9. The preburner $NO_x$ emissions are shown as engine exhaust concentrations and include a correction for secondary air dilution further downstream in the combustion system. The data in Fig. 7 show $NO_x$ emissions as a function of primary zone equivalence ratio. It was demonstrated that the primary stage has less than 1 ppm $NO_x$ for a wide operating range. The same data are plotted in Fig. 8 where $NO_x$ emissions are shown as a function of primary zone calculated adiabatic flame temperature. The preburner CO and unburned hydrocarbon emissions are not a critical consideration as these constituents are oxidized downstream in the catalytic reactor or the burnout zone.

The data in Fig. 9 were obtained at two sets of preburner inlet conditions. The 750 $^{0}$F and 804 $^{0}$F inlet temperature conditions represent 50 % and 100 % load, respectively for the T-70 engine. The primary stage data points shown in Fig. 9 are the same as the data discussed in Fig. 7 and 8. The secondary stage data points were collected by maintaining a fixed adiabatic flame temperature in the primary stage for each condition and adding fuel to the secondary stage in increments. The graph shows that the main contributor to overall $NO_x$ emissions is the primary stage. This means that as long as the primary stage is used to deliver less than 120 $^{0}$F temperature rise and additional fuel is added to the secondary stage to get the required preheat, the overall $NO_x$ emissions can be maintained significantly below 2 ppm. This is due to the fact that the secondary stage is always operating much leaner than the primary stage thus adding little or no $NO_x$ to the overall emissions.

## 2.2 Premixer Performance Tests

### Fuel Air Uniformity

The premixer performance was demonstrated at a scaled condition shown in Table 3. This condition simulated the fuel and air momentum ratio through the premixer for actual engine design condition. Mixture samples were collected at twelve radial and circumferential locations at the catalyst inlet face. The fuel-air mixture was analyzed with a non-dispersive infrared hydrocarbon analyzer. The data obtained from this test are plotted in Fig 10. The results indicate that premixer performance is within design criteria of -/+ 5 % uniformity at the catalyst inlet.

### Temperature Uniformity

The durability of the catalyst module is dependent on gas temperature uniformity at the inlet face of the catalyst module. The catalyst inlet face was instrumented with type-K thermocouples at various radial and circumferential locations. The tests were conducted at the operating conditions indicated in Table 1. Fig. 11 shows test results where the range of catalyst inlet temperatures measured is shown as a function of preburner temperature rise. The data indicate that the temperature variation for a wide range of preburner operation falls well within the design goals, thus suggesting good catalyst durability.

## 2.3 Burn Out Zone Performance

The BOZ liner temperatures were measured when homogeneous combustion was taking place downstream of the catalyst module. These data are plotted in Fig. 12 as a function of BOZ exit temperature. The data indicate that the BOZ liner operates at temperatures well below 1650 $^0$F.

## 2.4 Complete Combustion System Test

The complete combustion system was tested at the conditions shown in Table 1 (column 4). Tests were somewhat compromised by air leakage from the rig, which tended to overheat the combustor test cell but had no impact on combustor performance. To run for extended periods of time, it was necessary to run at a reduced preburner inlet temperature and somewhat lower combustor pressures. To compensate, the preburner was "over-fired" to obtain the desired design point catalyst inlet temperature. The measured data are plotted versus time in Fig. 13.

Figure 13 shows measured temperatures at several locations of the combustion system at varying catalyst fuel flows. The catalyst fuel flows were calculated from the temperature rise across the catalyst module, assuming 50% fuel conversion (based on sub-scale testing at Catalytica). The fuel flow data thus obtained matched fairly well with the fuel/air mixture data obtained from the hydrocarbon analyzer. The BOZ exit temperatures were measured using three type-S thermocouples. For the condition tested, data indicated a temperature rise of 500 $^0$F across the BOZ (see T2.5 in Fig. 13), indicating the start of homogeneous combustion downstream of the catalyst module. The design condition for the BOZ temperature rise was 805 $^0$F, which could not be tested due to cooling water limitations in the rig hardware.

The catalyst exit temperature uniformity was also assessed. During testing, approximately 50 % of the thermocouples on the catalyst module were damaged. However, the data shown in Fig. 14 indicate that the catalyst exit peak-to-peak temperature variation was approximately 50 $^0$F at an average catalyst exit temperature of 1650 $^0$F.

The emissions data obtained from the complete combustor tests are plotted in Fig. 15. This figure also includes data obtained from the preburner tests (same data as in Fig. 9) for comparison. The $NO_x$ emissions obtained from the full combustor tests are actually somewhat higher than would be obtained at the combustor design point due to the over-firing of the preburner (440 $^0$F versus 186 $^0$F). The plot shows that $NO_x$ emissions (corrected to 15% $O_2$) are well below 3 ppm. At the design preburner temperature rise of approximately 186 $^0$F, the preburner would produce less $NO_x$ and engine emissions should be even lower.

## 3. Conclusion

The prototype catalytic combustion system performed extremely well in the rig tests conducted at CTC. Virtually all of the design goals such as system pressure drop of less than 4 %, premixer fuel-air uniformity of ± 5 %, and $NO_x$ emissions of less than 2.5 ppm were satisfied. The individual components testing and testing of the entire combustion system demonstrated that $NO_x$ emissions could be kept below 3 ppm over a simulated range of engine load from 50 to 100%. Although the rig test facility could not reach the T-70 full load pressure (150psia versus 250 psia), component testing has indicated that $NO_x$ emissions are not strongly impacted by pressure. Thus the rig tests provide a high level of confidence that full pressure testing will be equally successful.

Of particular note was the excellent performance of the preburner and premixer. These critical components are largely responsible for the $NO_x$ generated by the combustion system. Specifically, the wide turndown demonstrated by the preburner is advantageous in extending the useful life of the catalytic reactor. As catalyst effectiveness decreases slowly with time, reactor performance can be recovered by increasing the preburner exhaust temperature. If the preburner can be fired at increasingly higher temperatures without exceeding $NO_x$ limits, the catalytic reactor will continue to function as required. The low $NO_x$ capabilities of the preburner suggest that the reactor should exhibit a functional life similar to levels seen by CESI in their Kawasaki system (~ 8000 hours).

Beyond this rig testing, an on-engine test of the combustion system is the next technical milestone for the combustion system. In order to meet this milestone, the design and manufacturing of the unique T-70 engine hardware needed for the catalytic combustor must be completed.

## 4. References


Nazeer, W., Solar Task 2.1.7 Preliminary Test Plan Component Test Plan – October 28, 2002.

Nazeer, W., Solar Task 2.4.1 High Pressure Test Plan – January 17, 2004

Spencer, M., Catalytica Energy Systems Inc., T-70C Catalyst Module Test Plan, Rev. D – February 24, 2004.

Nazeer, W., Fahme, A., and Smith, K., Engineering Design Memo 0043, Preburner Design and CFD Analysis for the Taurus 70 Catalytic Combustion System – March 02, 2004.

Nazeer, W. and Fahme, A., Engineering Design Memo 0044, Taurus 70 Catalytic Combustion System Atmospheric Test – March 08, 2004.


## Table 2: Preburner inlet test conditions

| T2.3 ($^0$F) | P2.3 (psia) | Wa (pps) |
|---|---|---|
| 600 | 150 | 24.8 |
| 750 | 175 | 24.8 |
| 804 | 175 | 25.8 |
| 850 | 175 | 25.8 |

Table 3: Premixer performance test condition

| T2.3 ($^0$F) | P2.3 (psia) | T2.5 ($^0$F) | Wa (pps) | Wf Mixer (pph) |
|---|---|---|---|---|
| 355 | 150 | 485 | 27 | 1200 |

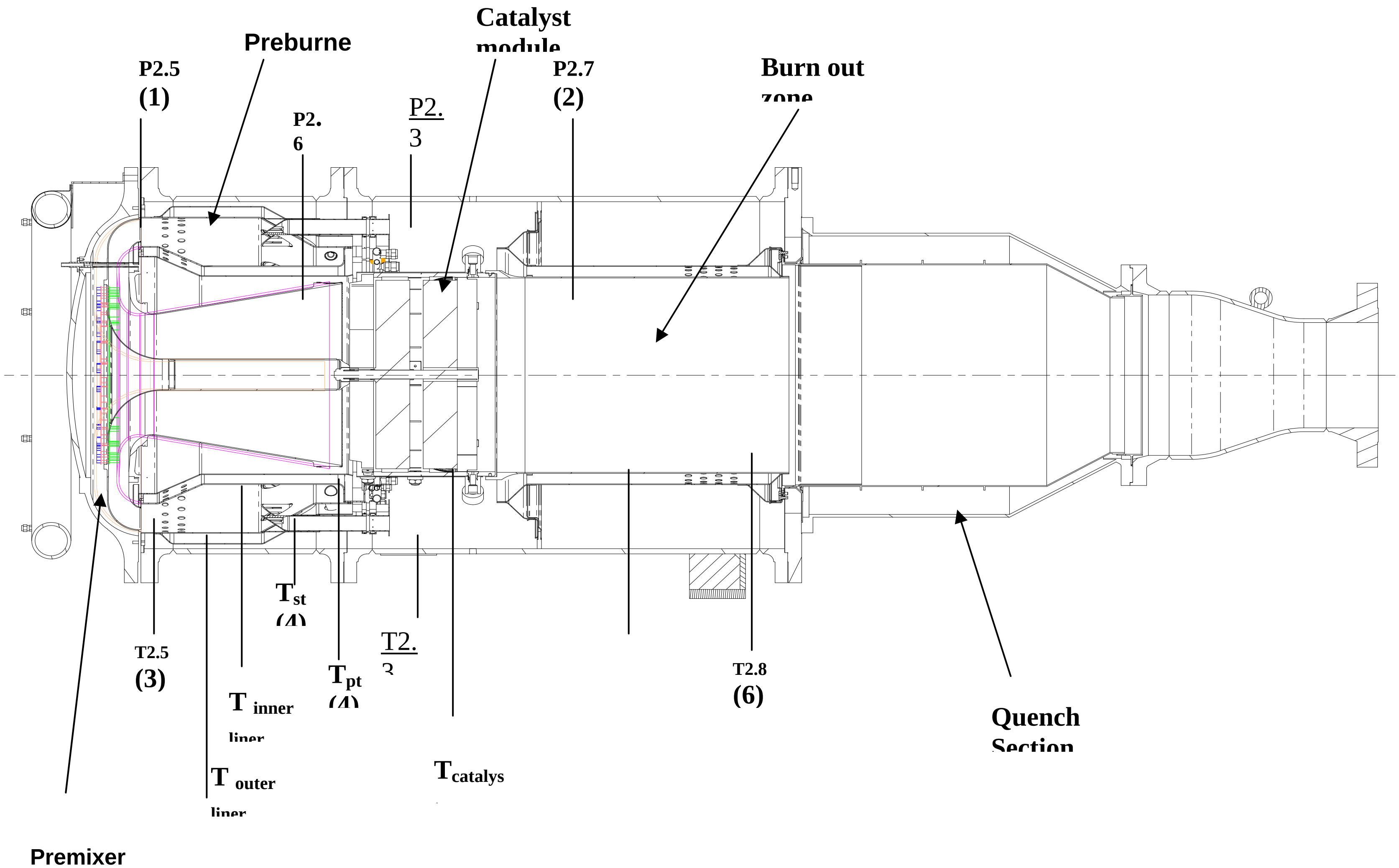



**Figure 1: Instrumentation locations for the complete combustion system**

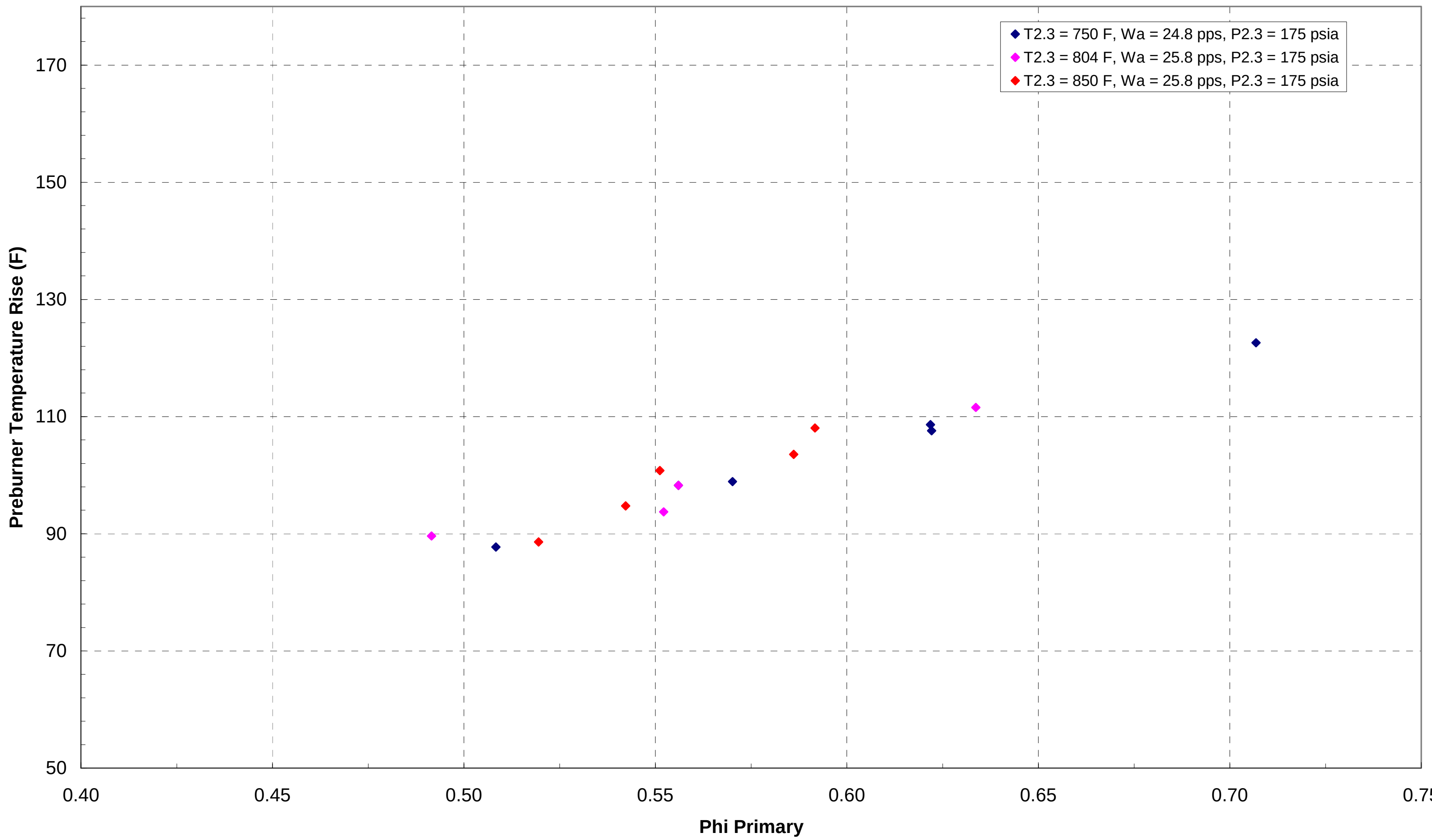



**Figure 2: Primary stage turndown at varying inlet conditions**

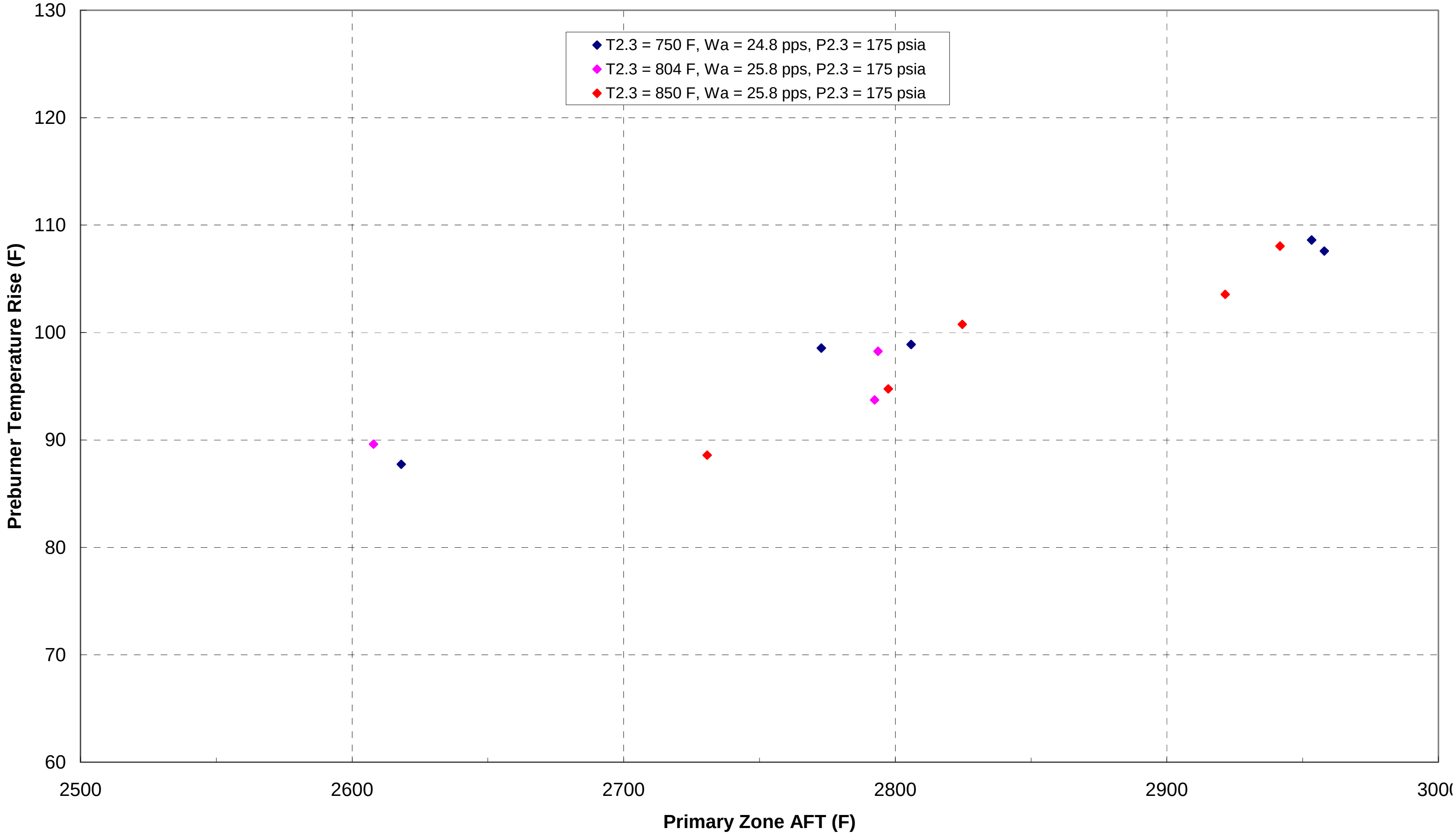



**Figure 3: Primary stage turndown at varying inlet conditions**

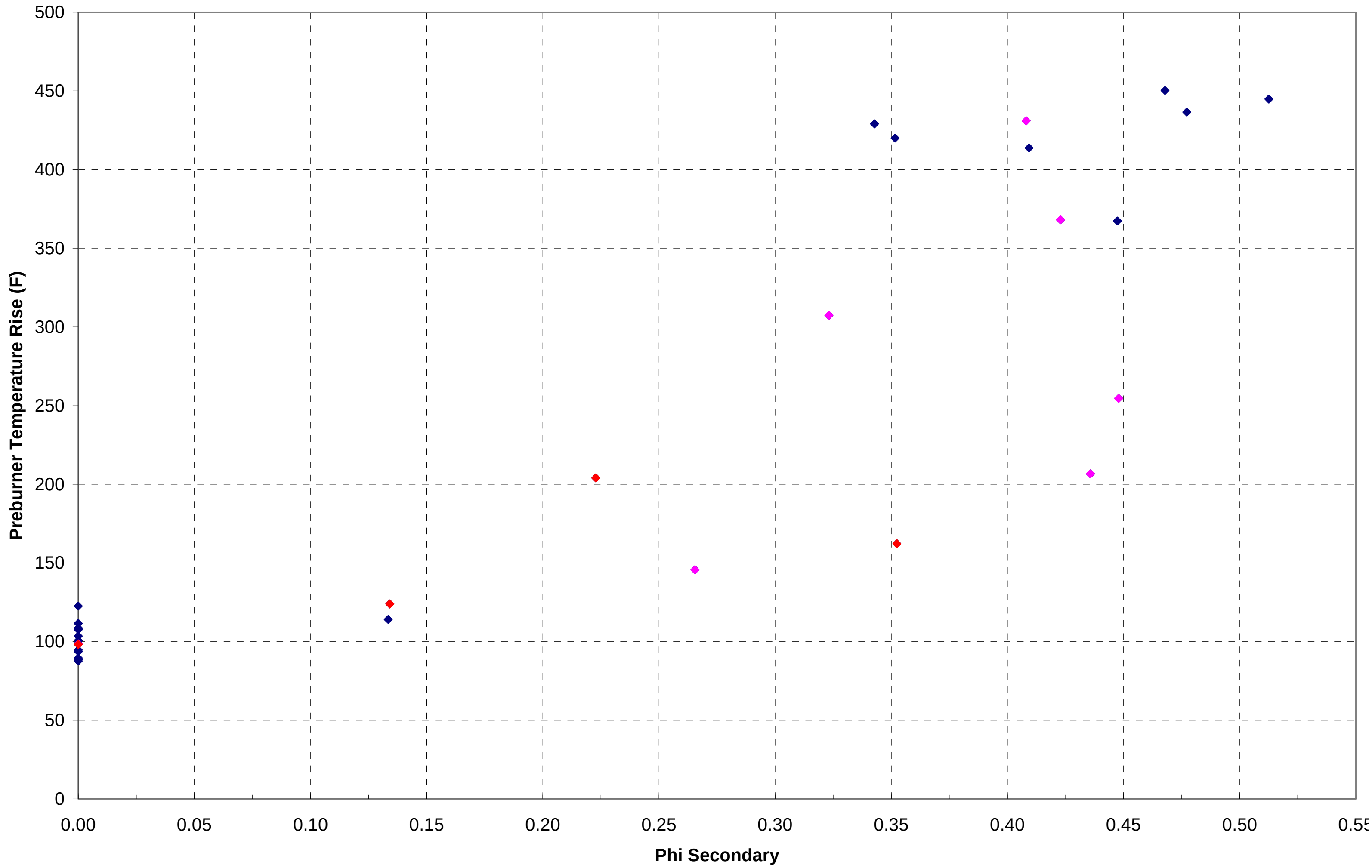



**Figure 4: Secondary stage turndown at varying primary stage equivalence ratios**

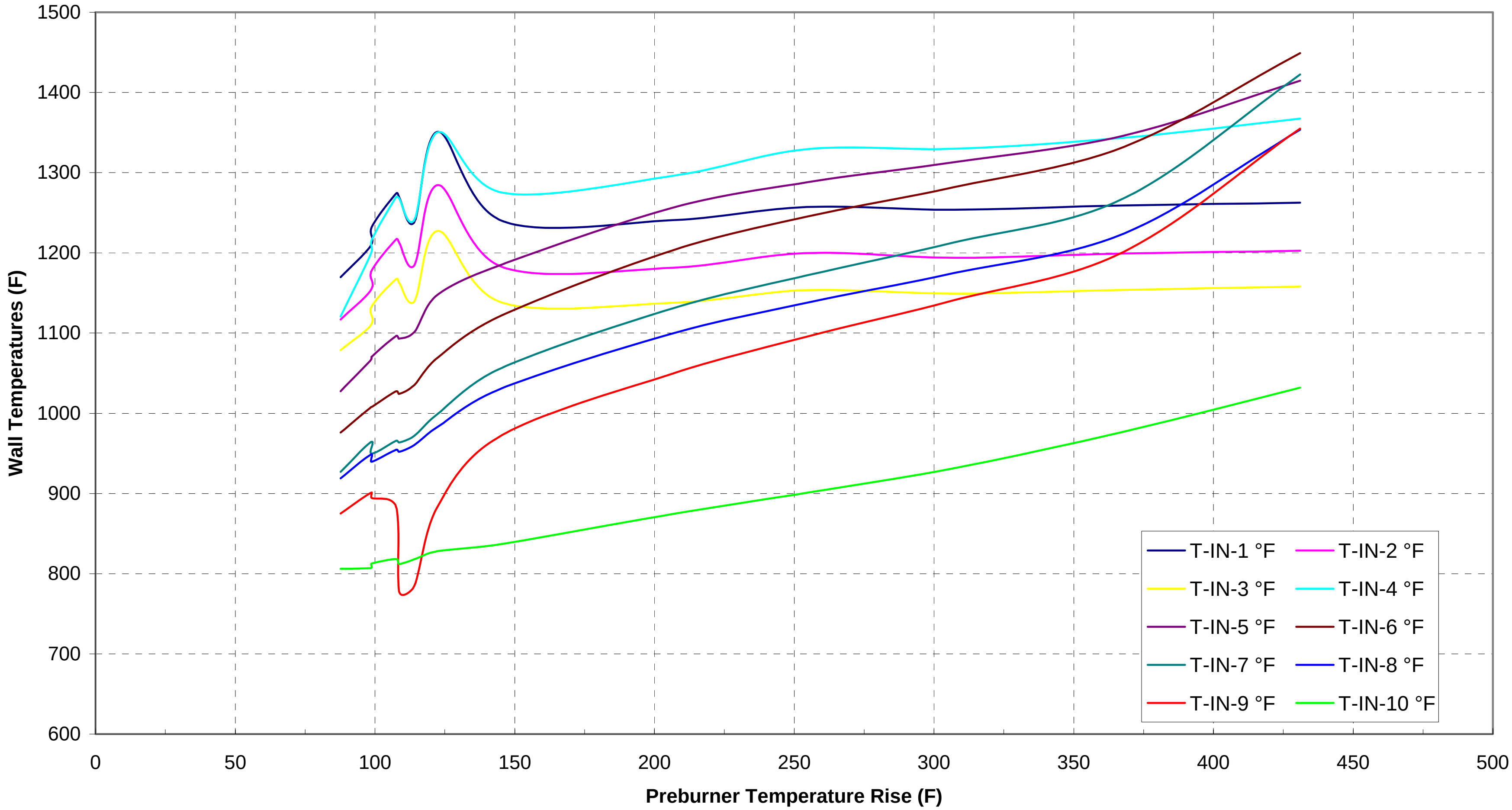



**Figure 5: Preburner inner liner wall temperatures as a function of temperature rise**

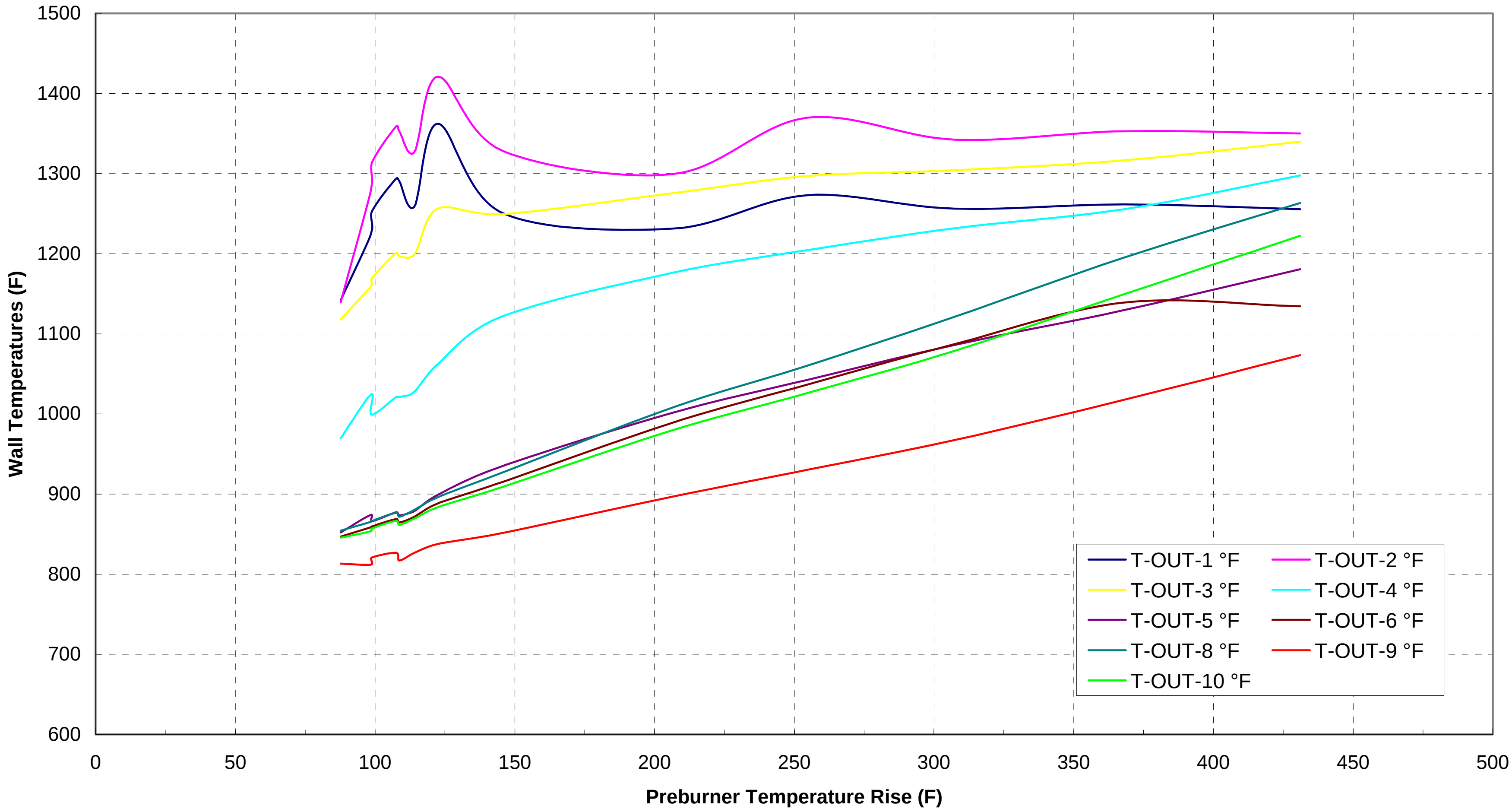



**Figure 6: Preburner outer liner wall temperatures as a function of temperature rise**

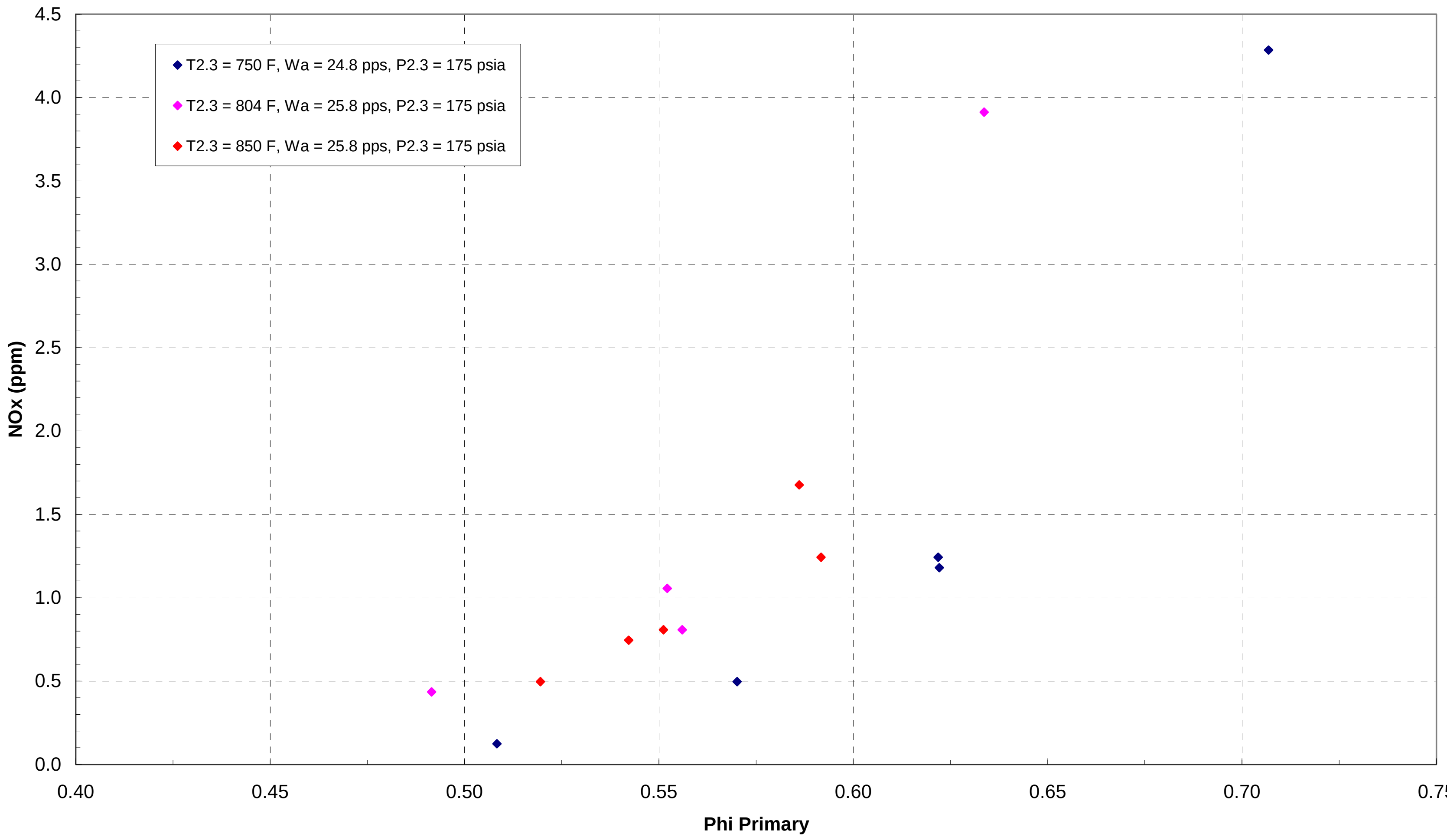



**Figure 7: Primary stage emissions corrected to 15 % $O_2$**

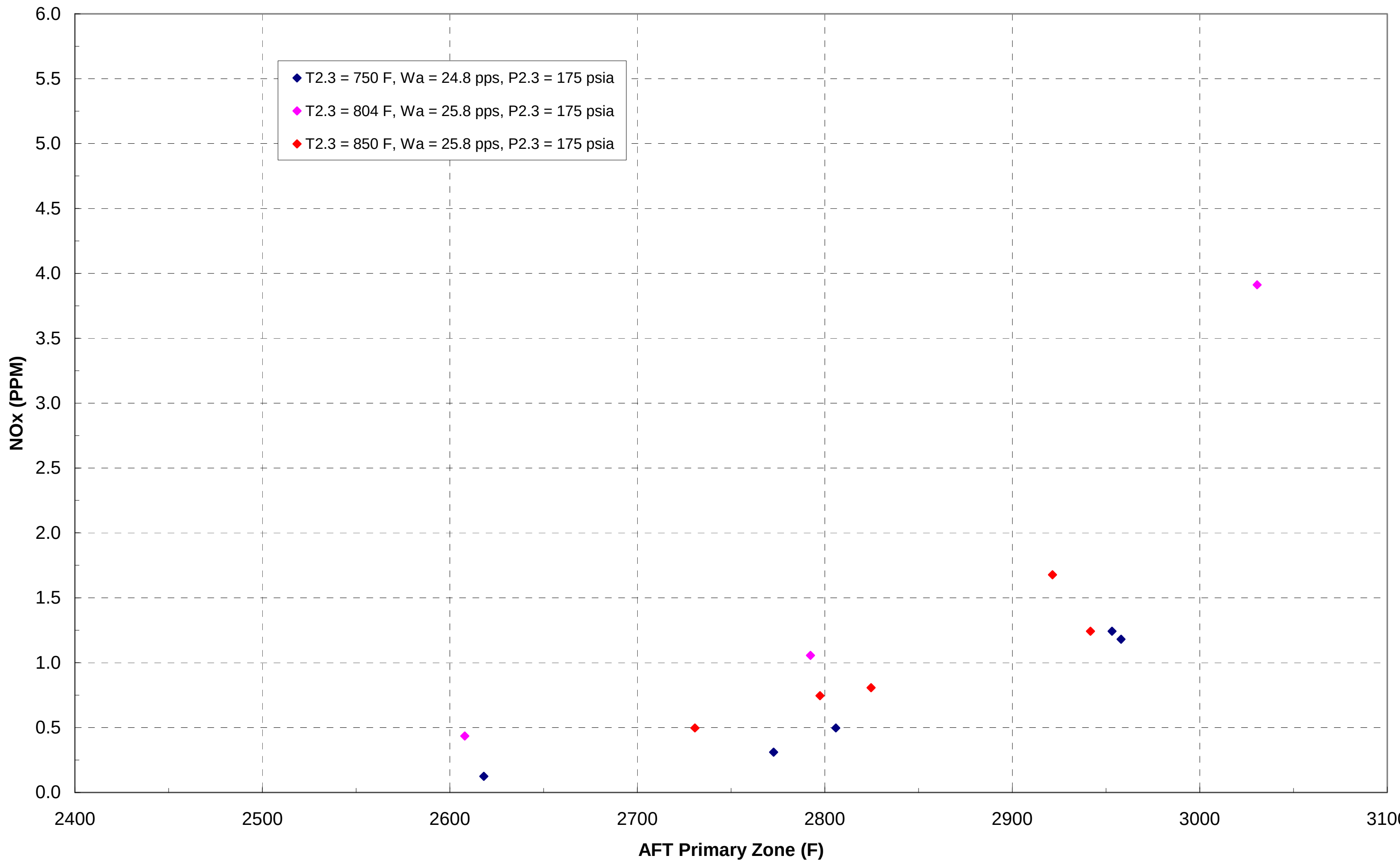



**Figure 8: Primary stage emissions corrected to 15 % $O_2$**

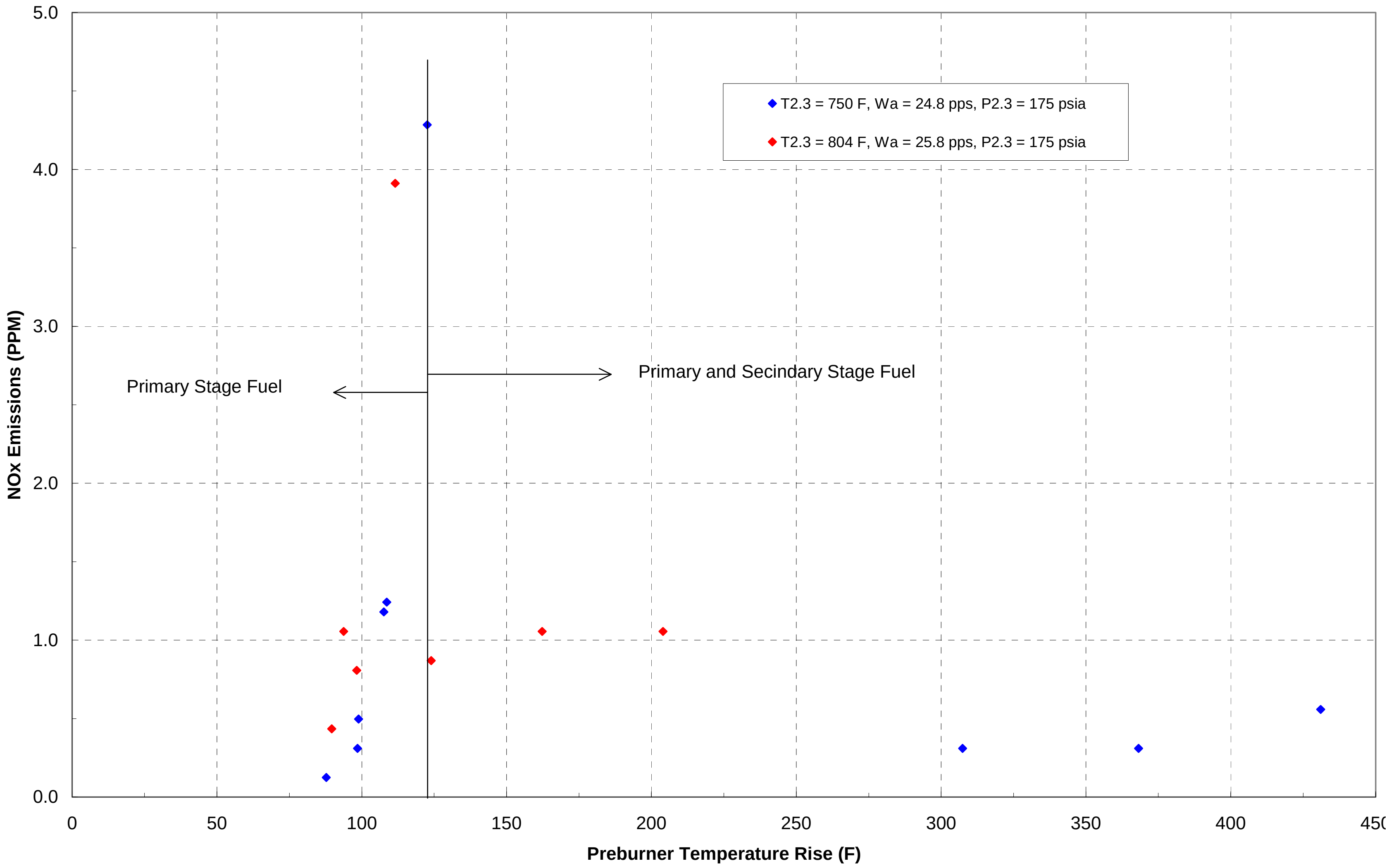



**Figure 9: Preburner overall emissions as a function of temperature rise**

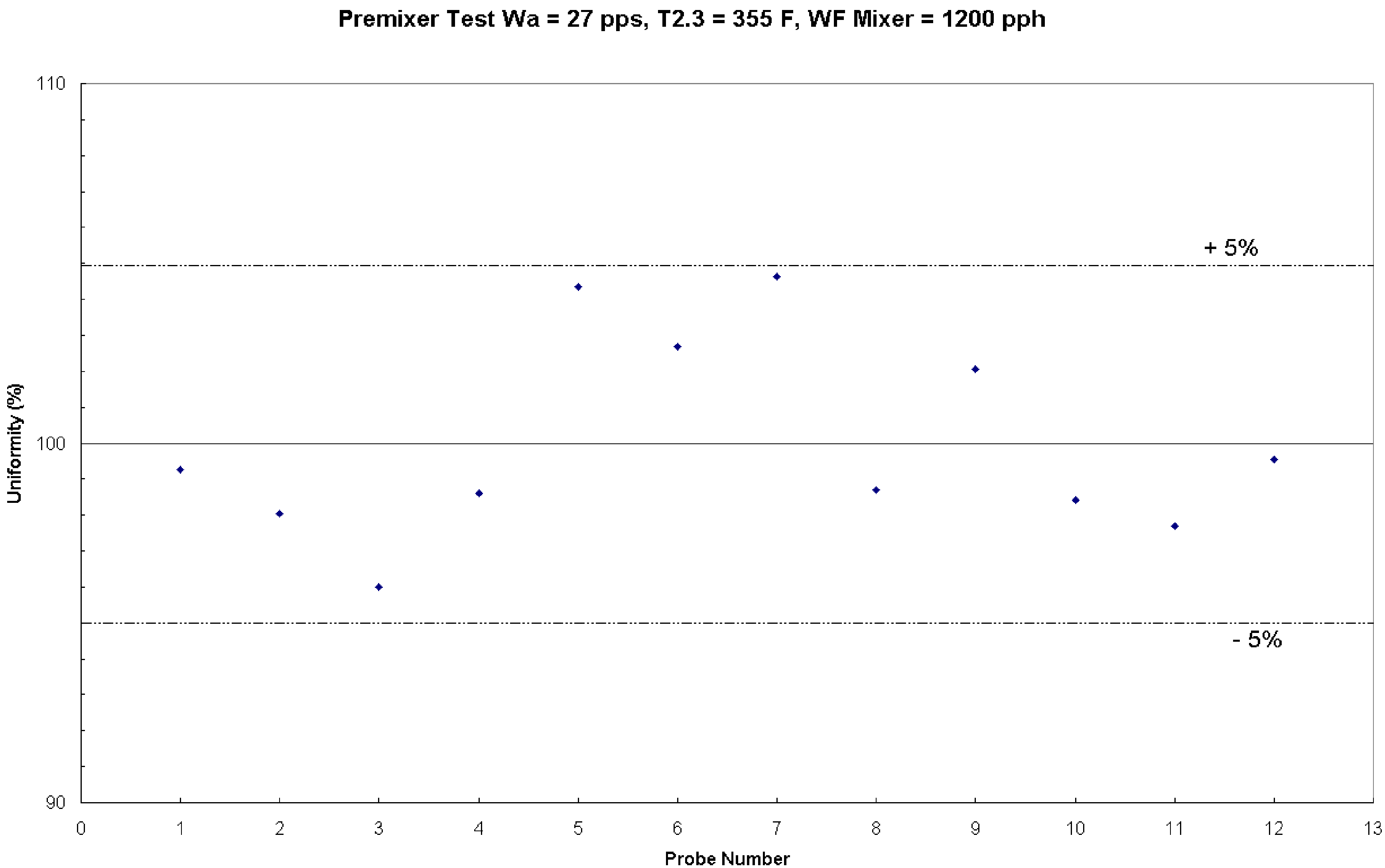



**Figure 10: Catalyst inlet fuel-air mixture uniformity**

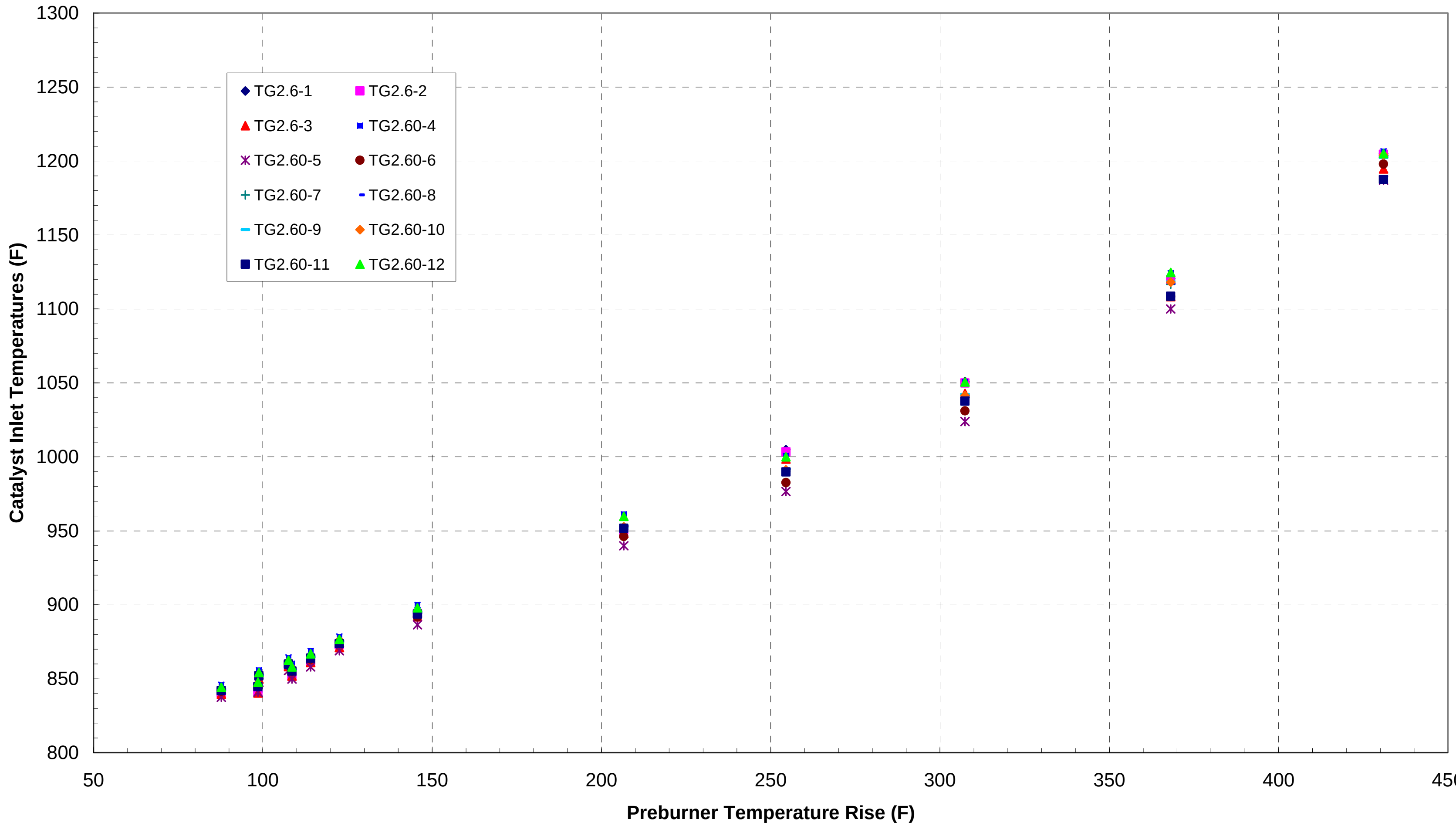



**Figure 11: Temperature uniformity at catalyst inlet face**

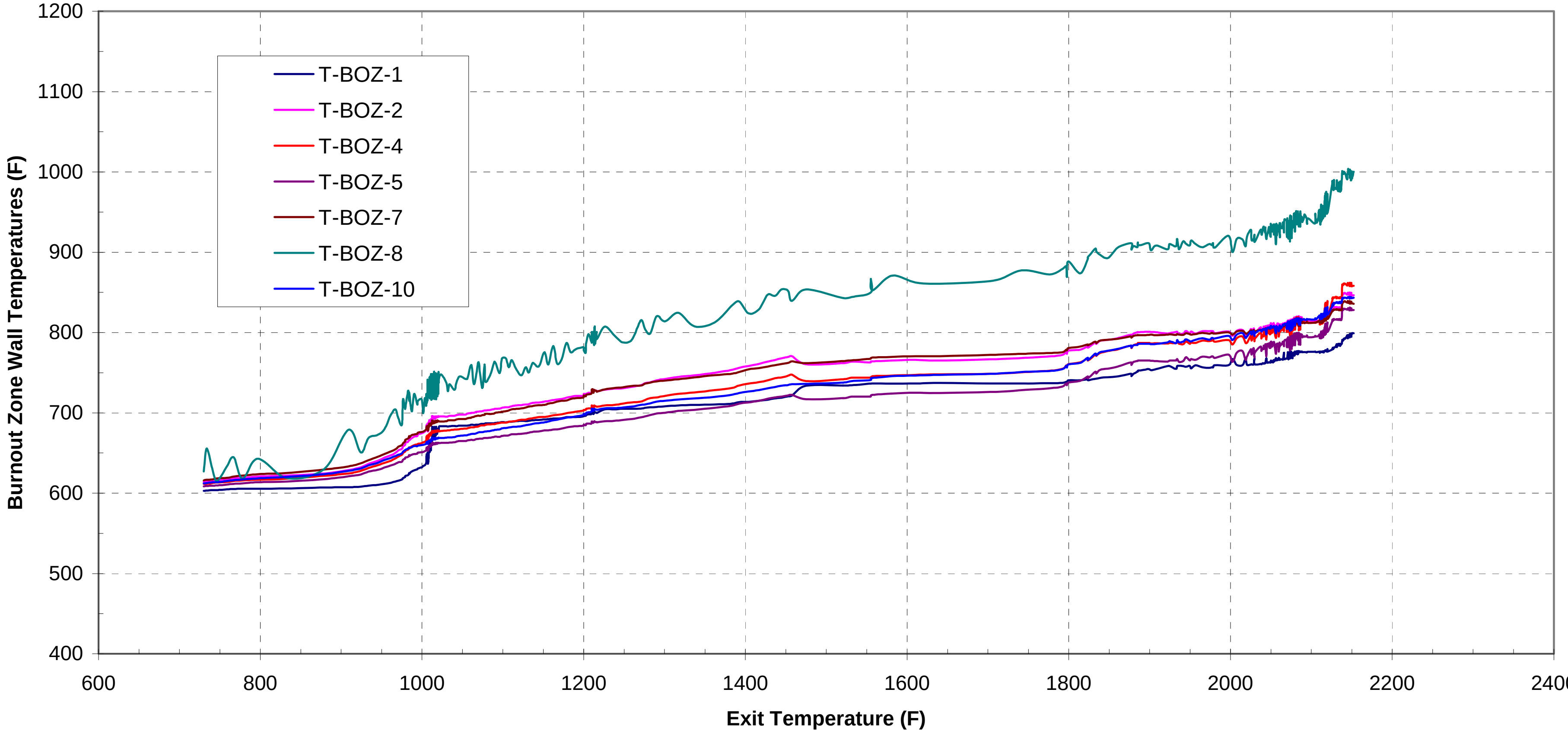



**Figure 12: Burnout zone wall temperatures with homogenous combustion**

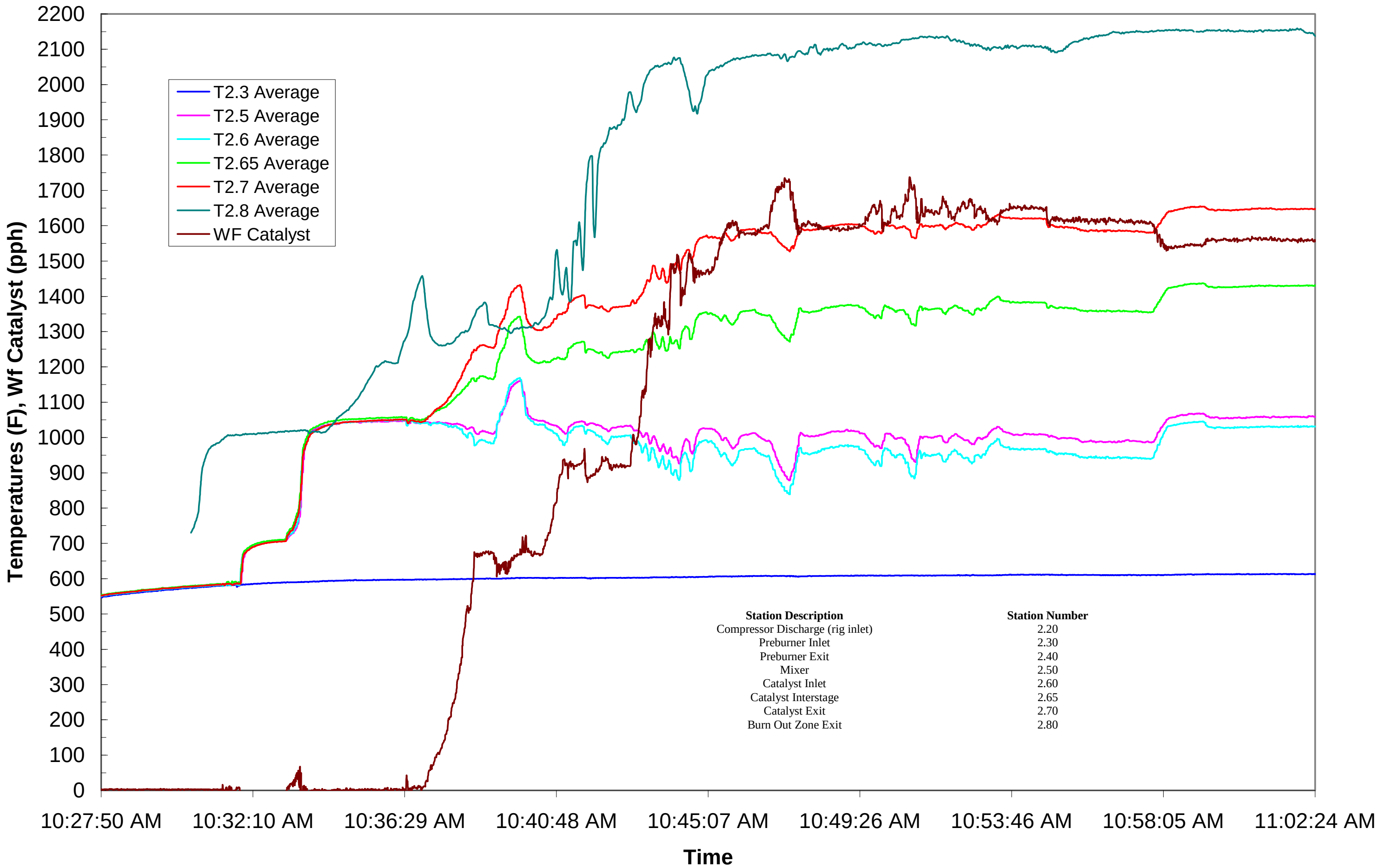



**Figure 13: Catalyst activity test at simulated full load catalyst inlet condition**

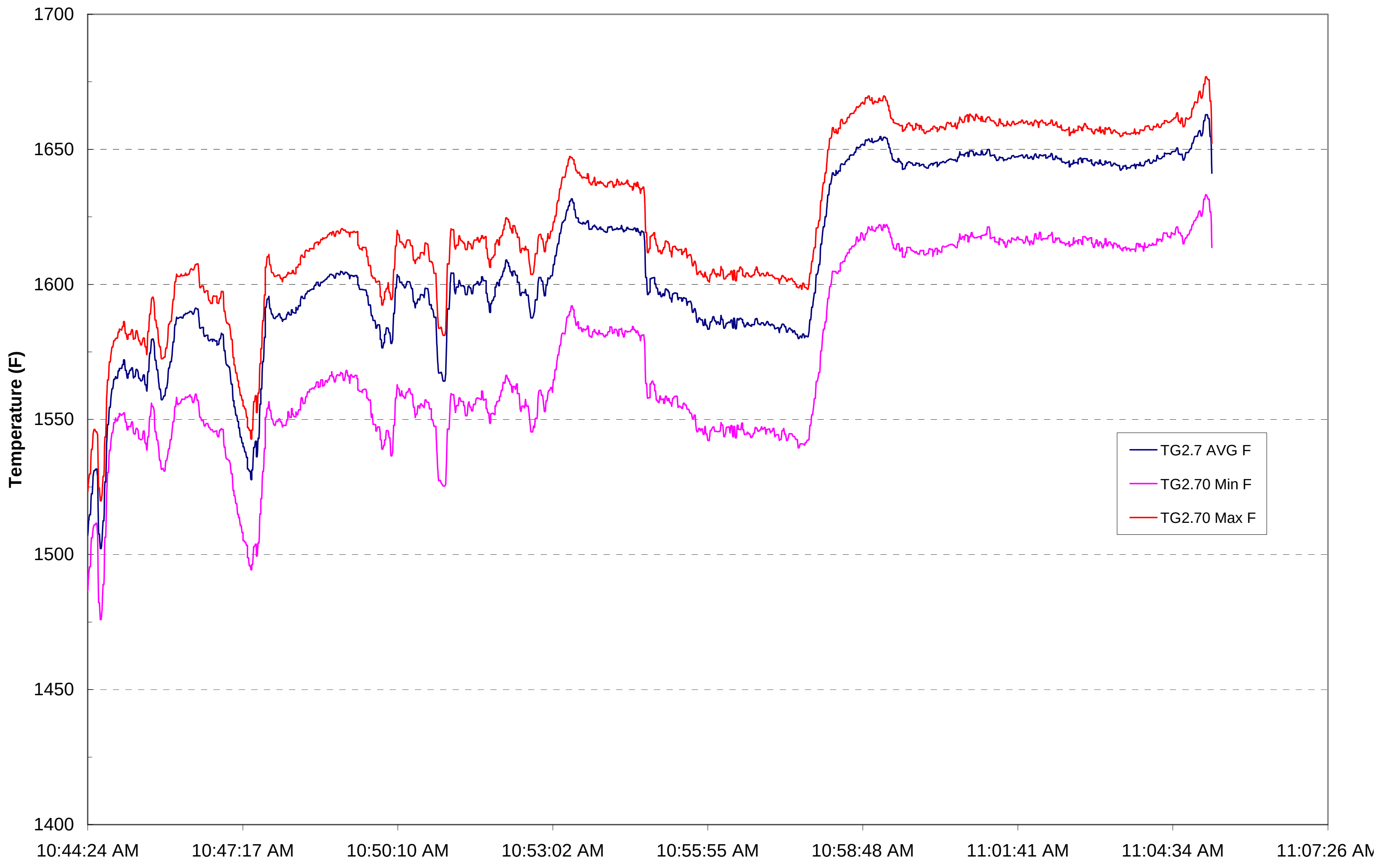



**Figure 14: Catalyst exit temperature uniformity**

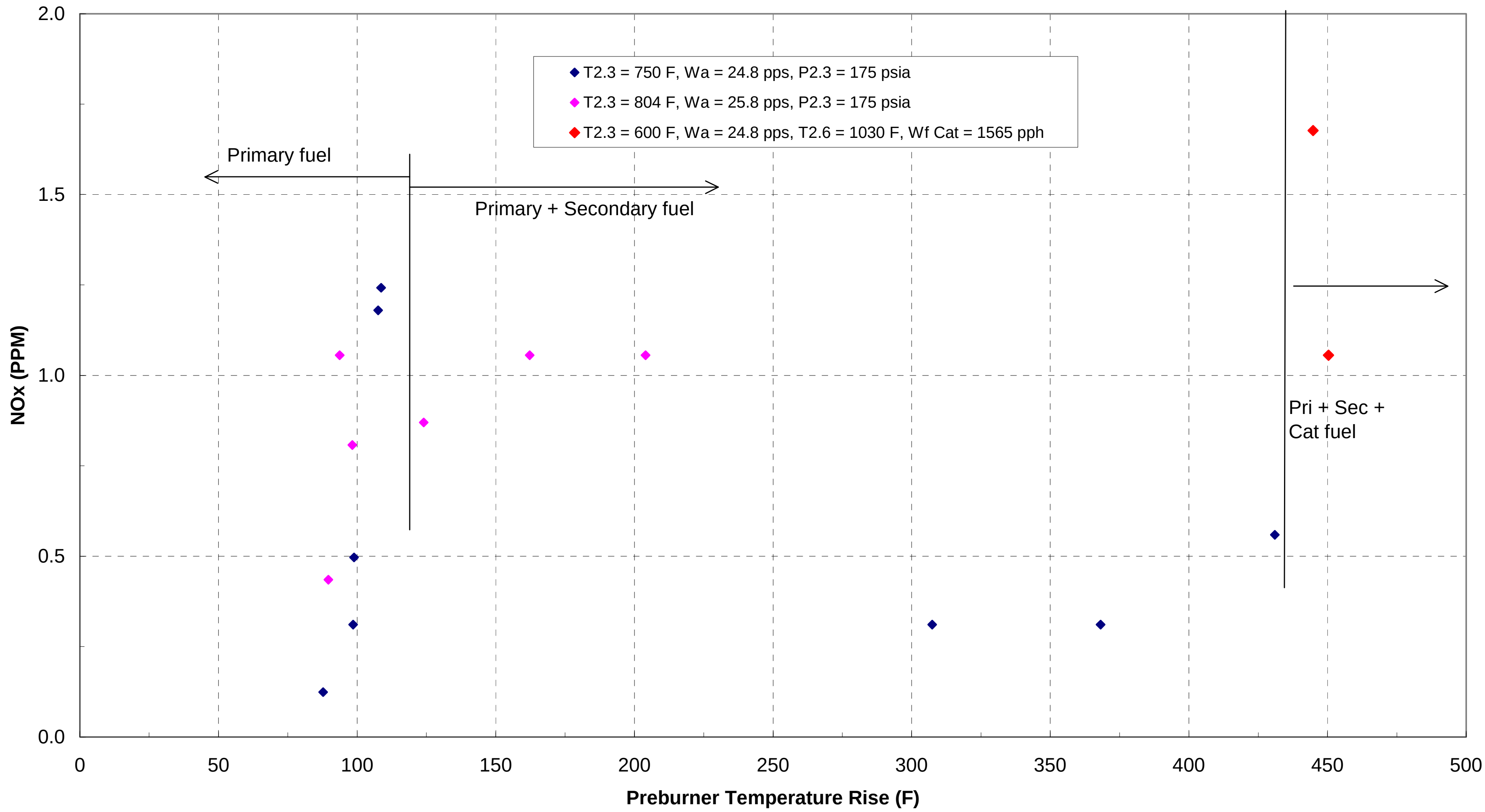



**Figure 15: Over all $NO_x$ emissions corrected to 15 % $O_2$**

## 8.7. Appendix II-A: Technology Transfer

# Engineering Research and Development Report

# TECHNOLOGY TRANSFER

## Catalytic Combustor-Fired Industrial Gas Turbine

**CEC Contract 500-01-045**

**Task 2.6**

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# SUMMARY

This Technology Transfer Plan (TTP) was prepared as part of the work conducted under California Energy Commission Contract 500-01-045. The focus of this project is to develop and demonstrate a prototype ultra-low $NO_x$ emissions combustion system for industrial gas turbines. The project focused specifically on adapting Alzeta Corporation's nanoSTAR™ surface combustion technology to Solar Turbines' Taurus 70 turbine (7.5 MW). The technology has broad application to other gas turbines as well.

The level of detail presented in the Solar Turbines TTP is consistent with the state of development of the technology. To date, two sets of nanoSTAR™ burners (twelve burners per set) have been manufactured for evaluation in test engines at Solar Turbines. Including early prototypes used for single burner combustor rig testing, approximately 50 burners have been fabricated as the burner design has evolved. Consequently, the technology is in an advanced stage of technical development but a relatively early stage of integration into the Taurus 70 engine. Long-term durability tests in field engines represent the last major technical hurdle before early commercial sales can begin.

This TTP is considered preliminary and it creates the framework for a more detailed TTP that will be developed as the nanoSTAR™ combustion system is qualified for commercial release through field testing.  It should be appreciated that, at this time, no decision has been made by Solar Turbines or Alzeta to move the technology to the market.  That decision will be based on a detailed assessment of factors related to technical performance, economics, market projections and air quality regulations.

## *Technology Transfer Plan*

The purpose of the Technology Transfer Plan (TTP) for the Taurus 70 (T-70) nanoSTAR™ combustion system is to identify the major elements of the strategy to disseminate the results of the project to gas turbine manufacturers, gas turbine operators (specifically the power generation industry), air quality regulatory agencies and the general public. Early exposure to the program technology will promote early consideration of an ultra-low $NO_x$ turbine product even as the technical development continues. Once the decision to commercialize the nanoSTAR™ technology for the T-70 has been made, the TTP is expected to foster rapid technology acceptance by the market place and to accelerate the product's early commercial sales. In time the TTP will evolve into a more product-specific marketing plan that will be focused on potential customers.

The level of detail in the preliminary TTP is consistent with the state of development of the nanoSTAR™ system. Presently, the technology is being evaluated at a "preproduction" level where limited quantities of parts are manufactured for non-commercial development testing. As the technology advances, a detailed product business plan will be developed and refined to support Solar Turbines' ultimate decision to commercialize the technology.

Once the commitment to a product has been made, the system will come to market as "early production" hardware. Limited numbers will be manufactured for commercial sale to allow any new product issues to be rectified. Subsequently, the product will move to "production" status with sales no longer being restricted.

Figure 1 illustrates the relationship between the technical development steps and the TTP activities. The activities defined as appropriate for the technology assessment/development stage are already being carried out. Appendix A lists the technical papers that have been prepared and presented to the gas turbine community at technical conferences. Appendix B illustrates the literature available through Alzeta that describes the nanoSTAR™ technology and its potential performance benefits. In addition, Alzeta has been proactive in disseminating information about the nanoSTAR™ technology through new technology competitions.

Once the commitment to production has been made, the TTP will encompass more traditional market-focused activities. Commercial sales will be sought through Solar Turbines product literature, advertising campaigns, displays at industry conferences, and direct contact with an established customer base. These activities are common with new product introductions at Solar Turbines and will follow Solar Turbines' established marketing strategy.

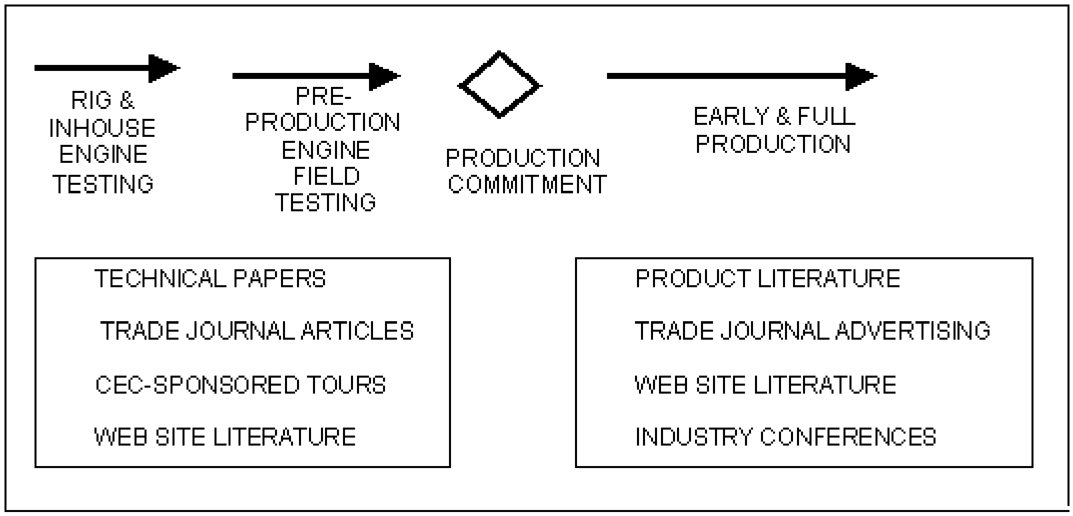



**Figure 35. Technology Transfer Plan Framework**

## Appendix A: Technical Conference Publications with Presentations

Arellano, L.O., Bhattacharya, A.K., Smith, K.O., Greenberg, S.J. and McDougald, N.K., "Development and Demonstration of Engine-Ready Surface-Stabilized Combustion System", ASME Paper # GT2006-91285, presented at the 2006 ASME Turbo Expo, Barcelona, Spain, May 8-11, 2006.

Greenberg, S.J., McDougald, N.K. and Arellano, L.O., "Full-Scale Demonstration of Surface-Stabilized Fuel Injectors for Sub-Three PPM $NO_x$ Emissions", ASME Paper # GT2004-53629, presented at the 2004 ASME Turbo Expo, Vienna, Austria, June 14-17, 2004.

Greenberg, S.J., McDougald, N.K., Weakley, C.K., Kendall, R.M. and Arellano, L.O., "Surface-Stabilized Fuel Injectors with Sub-3 PPM $NO_x$ Emissions for a 5.5 MW Gas Turbine Engine", ASME Paper # GT2003-38489, presented at the 2003 ASME Turbo Expo, Atlanta GA, June 16-19, 2003.

Weakley, C.K., Greenberg, S.J., Kendall, R.M., McDougald, N.K. and Arellano, L.O., "Development of Surface-Stabilized Fuel Injectors with Sub-3 PPM $NO_x$ Emissions", ASME Paper # IJPGC2002-26088, presented at the 2002 International Joint Power Generation Conference, Phoenix, AZ, June 24-26, 2002.

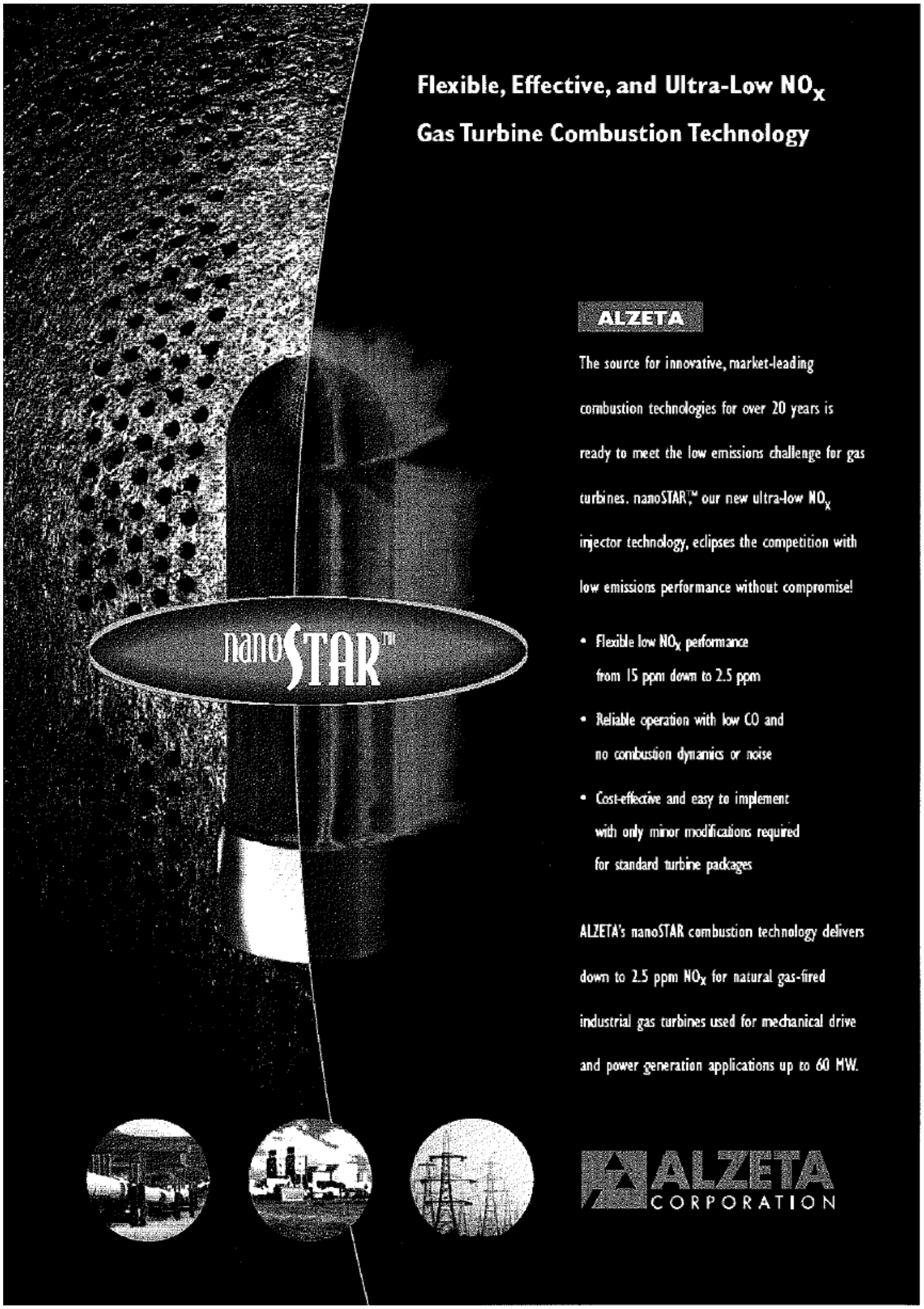
de Biasi, V., "Surface-Stabilized Burner Limits $NO_x$ to 3 PPM and CO to 10 PPM", Gas Turbine World, Vol. 34, No. 4, June - July, 2004.

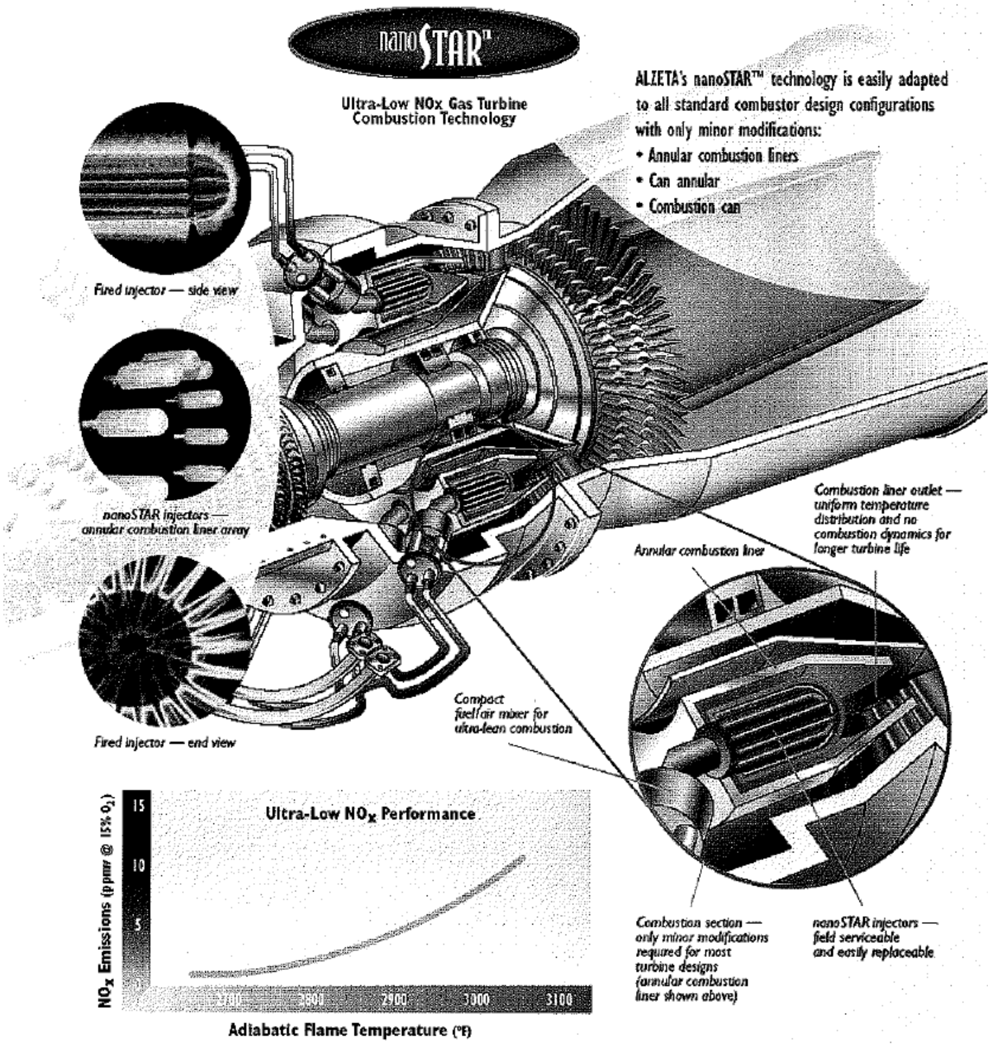
## Appendix B: Alzeta Sales Literature and Technology Awards

**<u>2003 Global Energy Awards</u>**

Alzeta's nanoSTAR™ Ultra-Low $NO_X$ Combustion Technology for Industrial Gas Turbines was selected as a finalist in Platt's Global Energy Awards as one of the Most Promising Pre-Commercial Technologies of the Year.

## Alzeta Sales Literature






ALZETA's nanoSTAR combustion technology delivers low emissions across a broad operating range. This provides greater flexibility in maintaining low emissions performance from full load down to part load operation and independent of fuel quality variability. In addition, nanoSTAR's surface-stabilized, premix operation eliminates combustion dynamics and noise, ensuring stable combustion and low CO emissions at very low adiabatic flame temperatures. nanoSTAR combustion technology is the affordable solution for turbine operators complying with a wide range of emissions regulations from 15 ppm down to 2.5 ppm.

ALZETA CORPORATION

*Advanced Combustion*
*Clean Air Solutions for Industry*

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## 8.8. Appendix II-B: Production Readiness Plan

# Engineering Research and Development Report

# PRODUCTION READINESS PLAN

## Catalytic Combustor-Fired Industrial Gas Turbine

**CEC Contract 500-01-045**

**Task 2.7**

Issued: November 9, 2007


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## SUMMARY

This preliminary Production Readiness Plan (PRP) was prepared as part of the technology development work conducted under California Energy Commission Contract 500-01-045. The focus of this project is to develop and demonstrate a prototype ultra-low $NO_x$ emissions combustion system for industrial gas turbines. The project focused specifically on adapting Alzeta Corporation's nanoSTAR™ surface combustion technology to Solar Turbines' Taurus 70 turbine (7.5 MW). The technology has broad application to other gas turbines as well.

The PRP encompasses only those manufacturing activities associated with Solar Turbines. A separate PRP has been prepared by Alzeta. It focuses on Alzeta's ability to provide the nanoSTAR™ burner elements on a commercial basis. The Alzeta plan was issued under Energy Commission Contract 500-01-010.

The level of detail presented in the Solar Turbines PRP is consistent with the state of development of the technology and Solar Turbines' expected scope of supply for the nanoSTAR™ combustion system. To date, two sets of nanoSTAR™ burners (twelve burners per set) have been manufactured for evaluation in test engines at Solar Turbines. Including early prototypes used for single burner combustor rig testing, approximately 50 burners have been fabricated as the burner design has evolved. Consequently, the technology is in an advanced stage of technical development but a relatively early stage of commercialization. Long-term durability tests in field engines represent the last major technical hurdle before early commercial sales begin.

In the early stage of production planning, the focus largely is on producibility evaluations for the pre-production hardware. Manufacturing feedback allows the engineer to optimize the design in terms of cost and performance.

The sourcing strategy adopted for production of the nanoSTAR™ system assumes the production of the surface burner elements by Alzeta. Alzeta would bear the responsibility of supplying components that meet the product specifications developed by Solar Turbines. The surface burner embodies the "new technology content" of the system. Other parts will be manufactured/ procured by Solar Turbines. These parts are very similar to components already being manufactured by Solar Turbines. Adequate facilities and a skilled work force are already in place. No new processes or unique materials will be utilized in the Solar Turbines manufacturing operations.

This preliminary PRP creates the framework for a more detailed PRP that will be developed as the nanoSTAR™ combustion system is qualified for commercial release through field testing.

## INTRODUCTION

The purpose of the preliminary Production Readiness Plan (PRP) for the Taurus 70 (T-70) nanoSTAR™ combustion system is to assess product manufacturing requirements relatively early in the development cycle. This allows early consideration of product manufacturability and early visibility of any manufacturing deficiencies that may exist. The PRP helps ensure a smooth product introduction and maximizes the product's potential for commercial success.

The level of detail in the preliminary PRP is consistent with the state of development of the nanoSTAR™ system. Presently, the technology is being evaluated at a "preproduction" level where limited quantities of parts are manufactured for non-commercial development testing. As the technology advances, the design will evolve to an "early production" stage. At this point, limited quantities will be manufactured for commercial sale. Subsequently, the product will move to "production" status with sales no longer being restricted. By then, the product will have been fully integrated into the routine sourcing and manufacturing infrastructure at Solar Turbines. Figure 1 illustrates the relationship between the technical and PRP activities.

At the preliminary PRP stage, the primary considerations include:

1. Any critical/strategic raw materials required
2. a sourcing/manufacturing strategy and the identification of any long lead items that will pace production
3. any new production processes or equipment that are necessary
4. any capacity constraints of existing equipment
5. need for additional manpower
6. hazardous or non-recyclable materials
7. capital spending needs to ramp from "early production" to "production"
8. preliminary production cost estimates

This preliminary PRP focuses on the manufacturing activities that Solar Turbines will undertake in moving the nanoSTAR™ combustion system to production. The current sourcing strategy is to purchase nanoSTAR™ burners from Alzeta; Solar Turbines will not be involved directly in their manufacture. In a separate Commission-funded project (Contract 500-01-010), Alzeta has addressed the PRP for the nanoSTAR™ burner elements themselves.

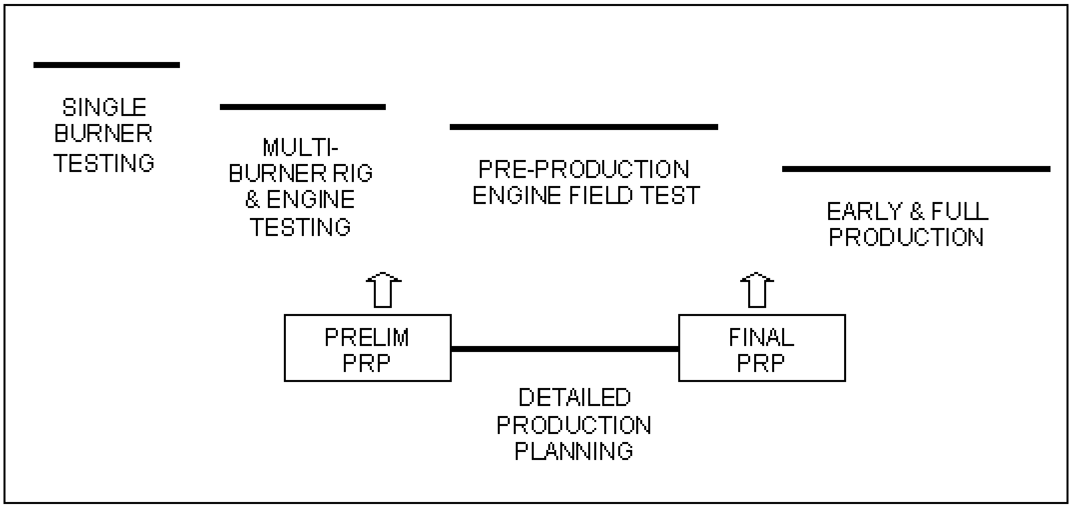


**Figure 1. Production Readiness Plan Approach**

## 2. PRODUCT DESCRIPTION

The Taurus 70 nanoSTAR™ combustion system is being developed for the California turbine market to provide an improved method of achieving ultra-low $NO_x$ emissions on natural gas fuel. Target $NO_x$ emissions are < 3 ppm (@15% exhaust $O_2$), which is consistent with $NO_x$ levels currently being achieved by downstream SCR systems. The nanoSTAR™ system is projected to be much less expensive than SCR. In addition, it will not result in the release of ammonia to the atmosphere as occurs with SCR systems. These advantages are expected to accelerate the use of clean gas turbines in California for high efficiency, industrial cogeneration.

The T-70 nanoSTAR™ burner module is comprised of three major elements (Fig 2):

- a porous surface burner element
- a pilot burner that supports the combustion process during transient operation
- a fuel/air premixer that is located upstream of the surface burner.

The T-70 requires twelve burner modules (Fig 3). The modules are installed in an annular combustor liner that contains the combustion process and exhausts the combustion products to the turbine section of the engine.

The nanoSTAR™ technology was developed by and is the intellectual property of Alzeta. The pilot burner and fuel/air premixer designs were developed by Solar Turbines as part of Energy Commission projects.

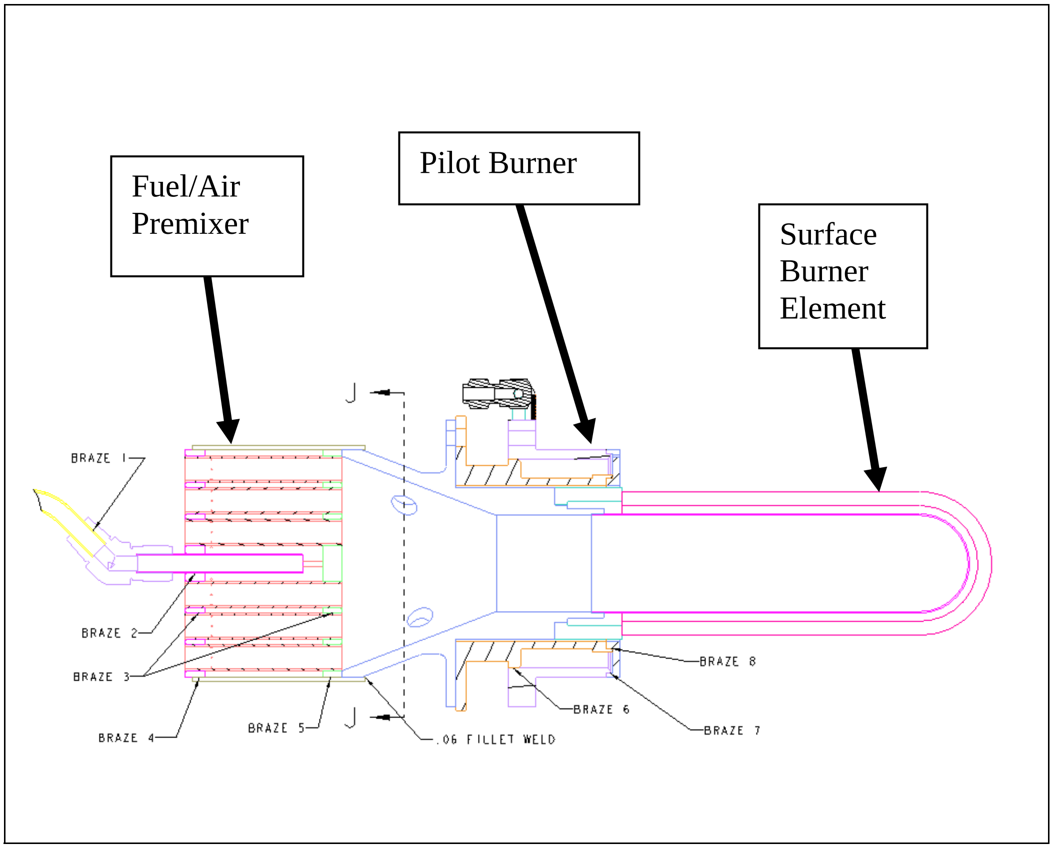


**Figure 36. T-70 nanoSTAR™ Surface Burner Module**


**Figure 3. Taurus 70 nanoSTAR™ Combustion System (view looking downstream)**

## 3. MANUFACTURING SUMMARY

The preferred strategy for Solar Turbines to produce the nanoSTAR™ burner modules is through a combination of internal manufacturing and external procurement. The nanoSTAR™ burner elements will be purchased from Alzeta for both new and replacement applications. The pilot burners and the premixers will be manufactured by Solar Turbines as this leverages Solar Turbines' in-house machining facilities and expertise. Final assembly of the burner components will be completed by Solar Turbines. Performance testing of the premixers, preburners and final burner modules will also be conducted by Solar Turbines. Inspection and qualification of the surface burner elements will be conducted by Alzeta.

### 3.1 CRITICAL PROCESSES

Initial analysis indicates that there are no critical materials, processes or facilities involved in the production of the Solar Turbines-owned components. The premixers and pilot burners will be manufactured using materials, methods and equipment already in use at Solar Turbines. As with current production parts, the manufacture of certain piece parts of the premixers and pilots may be out-sourced to qualified vendors, if cost savings can be realized. Final assembly of the components will be done at Solar Turbines using in-place brazing and welding capabilities.

### 3.2 MANUFACTURING AT ALZETA

Alzeta will be the supplier of the surface burner elements. As mentioned above, Alzeta has already published a PRP focused on surface burner manufacturing under Energy Commission contract 500-01-010.

A potential concern for Solar Turbines is the sole-source nature of the future procurement relationship with Alzeta. There is always risk associated with the use of a single supplier for critical components from both the supply and price escalation perspectives. Solar Turbines will work to structure a long term supply agreement that addresses price stability and an option for technology licensing in the event that Alzeta is unable to meet Solar Turbines' required production schedules.

Alzeta's nanoSTAR™ surface burner is a derivative of other porous burner products that have been in production by Alzeta for many years. Although relying on a single source is a concern, Solar Turbines believes Alzeta is well qualified to manufacturer the surface burner elements to Solar Turbines' specifications and to ramp up production as demand grows.

## 4. SOLAR TURBINES MANUFACTURING CAPACITY

Solar Turbines' current manufacturing capacity is adequate to supply the projected product volumes without impacting other production activities. The total manufacturing time in any work center will be small due to relatively low initial product volumes.

## 5. RECYCLING AND HAZARDOUS MATERIALS

There are no hazardous materials associated with Solar Turbines' manufacturing of the surface burners. Recycling of Solar Turbines parts will be minimal as both the premixers and pilot burners are expected to have service lives comparable or greater than the current production combustor liner (30,000 hours).

At present, the service life of the burner elements has not been established. As a minimum, burners will need to last 8,000 hours to be considered commercially viable. The burner elements will be replaced during scheduled overhauls in the field. Old burners will be recycled by Solar Turbines or returned to Alzeta for disposal if appropriate.

## 6. PRODUCT COST ESTIMATES

On a preliminary basis, Alzeta has estimated the cost of nanoSTAR™ injectors at $6,000 to $10,000 per megawatt. For the T-70 this would suggest a maximum cost of approximately $6,000 per burner module ($72,000 per burner set). This cost would be offset significantly by the avoided cost of the $SoLoNO_x$ fuel injectors that are replaced. Additional cost is associated with the preburners and premixers, but these costs are envisioned as being no greater than the cost of the burner elements themselves.

Solar has not established pricing for the nanoSTAR™ combustion system for several reasons. It is still unclear whether the technology can be integrated into the existing combustion system geometry or whether a transition to a canted liner will be necessary. Clearly the former would be much less costly in terms of non-recurring engineering and ultimate product pricing. In addition, the service life of the nanoSTAR™ burners will need to be established to guide pricing. Shorter service life will be reflected in higher O&M costs, which will put pressure on first cost. If the Alzeta nanoSTAR™ service life exceeds 8000 hours, the combustion system will provide a significant cost advantage to gas turbine users relative to current SCR systems.

## 7. SUMMARY

The nanoSTAR™ burner design has been proven in a series of rig and engine tests. Additional work is ongoing to develop a smaller premixer to simplify the integration of the burner into the Taurus 70. With the development of a second generation premixer, the design will be suitable for field tests. A design assessment indicates that there are no significant manufacturing barriers to commercialization of a Solar Turbines T-70 gas turbine equipped with an Alzeta nanoSTAR™ combustion system. Similarly, derivative applications to other medium-sized industrial engines will not require any significant changes in the turbine manufacturing process.

### 7.1 CONCLUSIONS AND RECOMMENDATIONS

The nanoSTAR™ technology has advanced to preproduction status. The surface burner element design is essentially fixed. Further work is being conducted on the premixer and preburner. This work is focused on maintaining (or improving) performance while down sizing the components for use with the production liner geometry.

Even with the current uncertainty about the premixer and preburner design detail, it is clear that the manufacturing requirements of these components can be met with Solar Turbines' current facilities and work force.

In production, there will be a significant reliance on Alzeta as the outside supplier for the major element of the combustion system. Establishing the sourcing relationship and monitoring product quality and delivery of the nanoSTAR™ burners will be a key element of product success.

Preliminary should-cost assessments of the system components indicate that the nanoSTAR™ system will be cost competitive with currently available SCR technology. Burner service life remains the major performance unknown at the present time.

## 8.9. Appendix II-C: Atmospheric Pressure Testing

# Engineering Research and Development Report

# Atmospheric Pressure Test Report

## Catalytic Combustor-Fired Industrial Gas Turbine

## CEC Contract: 500-01-045

**Task 2.5.1**

**Issued:** September 11, 2006

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**Nomenclature**

| | |
|---|---|
| Ae | Effective area |
| AFR | Air-to-fuel ratio by mass |
| Alpha | Percent of total combustion air flowing through burners |

$$\text{Alpha} = \frac{\sum Ae_{burner}}{\sum Ae_{burner} + Ae_{comb}}$$

| | |
|---|---|
| LBO | Lean blowout |
| SN | Serial number |

<u>subscripts</u>

| | |
|---|---|
| burner | burner air side (single burner) |
| comb | combustor liner |
| main | main fuel circuit |
| pilot | pilot fuel circuit |

## 1.0 Introduction

Atmospheric pressure combustion tests have been completed to qualify the T-70 surface-stabilized combustion system prior to being evaluated on an engine. These full-scale system tests have served to successfully validate functionality, performance, and minimum durability criteria.

## 2.0 Test Objectives

Experiments were conducted in an atmospheric combustion test rig with full-size engine hardware (Figure 1). The tests were done at actual engine temperatures and airflow rates scaled to atmospheric pressure. The tests served to:

- Characterize combustor metal temperatures
- Qualify combustor dome short term durability
- Characterize the combustor outlet (gas) temperature profile and pattern factor
- Characterize fuel-air distribution (injector to injector)
- Assess reaction uniformity (injector to injector)
- Validate system pressure drop and air flow splits
- Characterize emissions and lean stability limits at engine inlet temperatures corresponding to 50%, 75%, and 100% load
- Qualify the ignition system and define optimal settings for torch light-off
- Demonstrate system light-around on 100% pilot fuel
- Verify adequate combustor stability on pilot fuel only and demonstrate transition from pilot to main fuel at elevated inlet temperatures (corresponding to 50% engine load conditions).

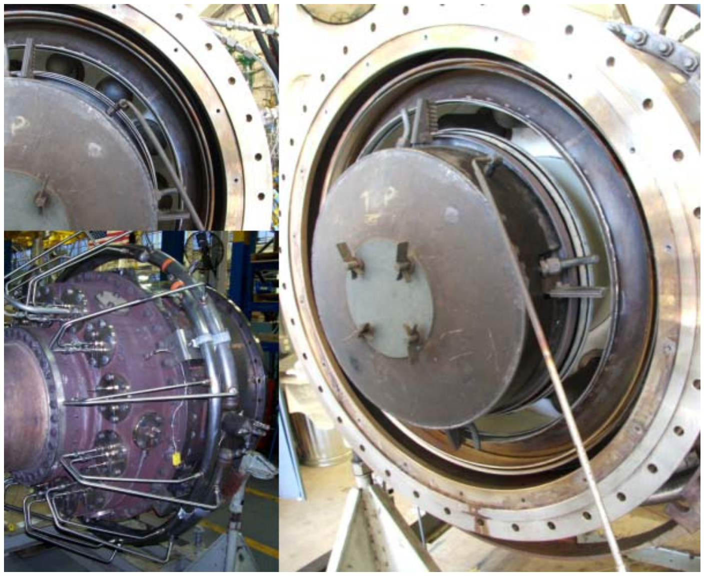


Figure 1. Atmospheric Full-Scale Combustion Test Rig

## 3.0 Test Results

Atmospheric test results are summarized in this section.

### 3.1 Cold Flow Evaluations

The effective areas of the burners and combustor were characterized prior to conducting combustion tests. Evaluations were completed in a cold-flow (non-reacting) test bench. The bench consists of calibrated mass flow instrumentation that enables the effective areas of components to be determined by measuring the pressure drop generated across the hardware by a known amount of airflow. Cold flow tests were used to assess the uniformity of the injector set, as well as the overall injector-to-liner flow split.

Table 1 summarizes the injector and combustor effective areas characterized. The air-side effective area results indicate that 71% of total combustor air flow will flow through the injectors. This is very close to the design target of 70%. On the fuel side, main and pilot injector effective areas are within 4% of the design targets. The resulting variation in the (premixed) main burner air-to-fuel (AFR) ratio is also within 4%. With the variation observed, it is expected that the coldest and hottest burners will operate approximately +/- 50 °F from the design flame temperature of 2750°. The magnitude of this potential variation should not prevent emissions targets from being met.

**Table 1. Hardware Effective Areas**

| Brn SN | Brn.Ae | Main.Ae | Pilot.Ae | AFR.Main |
|---|---|---|---|---|
| | in² | in² | in² | |
| B086 | 1.932 | 0.025 | 0.014 | 76.46 |
| B082 | 1.989 | 0.025 | 0.015 | 78.17 |
| B088 | 1.978 | 0.025 | 0.014 | 78.28 |
| B078 | 1.994 | 0.025 | 0.014 | 78.94 |
| B084 | 2.002 | 0.025 | 0.014 | 79.04 |
| B089 | 2.005 | 0.025 | 0.015 | 79.66 |
| B081 | 1.985 | 0.024 | 0.014 | 81.73 |
| B087 | 2.000 | 0.025 | 0.014 | 79.17 |
| B077 | 1.992 | 0.025 | 0.014 | 79.00 |
| B085 | 1.991 | 0.025 | 0.014 | 78.42 |
| B083 | 1.996 | 0.026 | 0.014 | 78.26 |
| B076 | 2.002 | 0.026 | 0.014 | 77.80 |
| Average | 1.989 | 0.025 | 0.014 | 78.75 |
| St Dev | 0.020 | 0.0003 | 0.0003 | 1.25 |
| Delta.min | 2.9% | 3.9% | 3.6% | 2.9% |
| Delta.max | 0.8% | 1.9% | 4.3% | 3.8% |

| | |
|---|---|
| Combustor Ae [in²] | 9.70 |
| Alpha | 71% |

### 3.2. Combustion Evaluations

Combustion tests were conducted to evaluate ignition, light-around, flame stability, combustor exit temperature distribution, and emissions at different simulated engine conditions. Table 2 summarizes the type of information gathered. Actual test results are summarized and discussed in the sections that follow.

**Table 2. Summary of Combustion Tests**

| Test | Information Produced |
|---|---|
| Igntion | Reaction Uniformity, Ignition Ease, Light-Around |
| 0% Load | Pilot Flame Stability |
| 50% Load | Combustor Exit Temperature Profile and Pattern Factor, AFR Uniformity, Reaction Structure, Emissions and LBO Limit, Light-Around Transition from Pilot to Main |
| 75% Load | Combustor Exit Temperature Profile and Pattern Factor, AFR Uniformity, Reaction Structure, Emissions and LBO Limit |
| 100% Load | Combustor Metal Temperatures (Thermal Paint Test), Combustor Exit Temperature Profile and Pattern Factor, AFR Uniformity, Reaction Structure, Emissions and LBO Limit |

### 3.2.1 Ignition Results

System ignition was found to be smooth, rapid, and reliable. Tests were conducted at engine ignition conditions with all fuel flowing through the pilot injectors. Ignition was initiated with the use of a production torch. Torch performance was reliable and allowed for rapid and reliable ignition of the combustion system.

Light-around of all twelve pilots occurred smoothly within about 2 seconds of initial pilot light off. In Figure 2, a star indicates the time at which the first injector became active. This event was also reflected in an average rise in combustor exit temperature, compared to the inlet air temperature, of about 400°F (Delta T). Light off of all pilots occurred at a fueling rate corresponding to a calculated flame temperature of 1000°F. Once all the pilots became active, the system remained self-sustained (without the torch) and stability at the acceleration condition corresponding to a flame temperature of 2200° F was easily met.

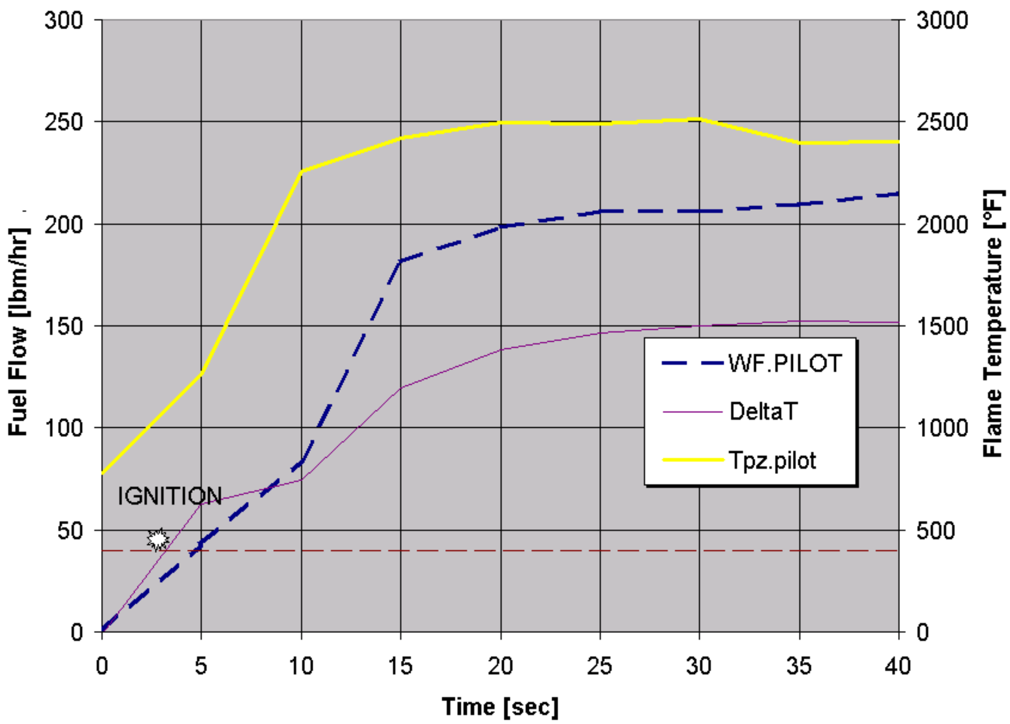
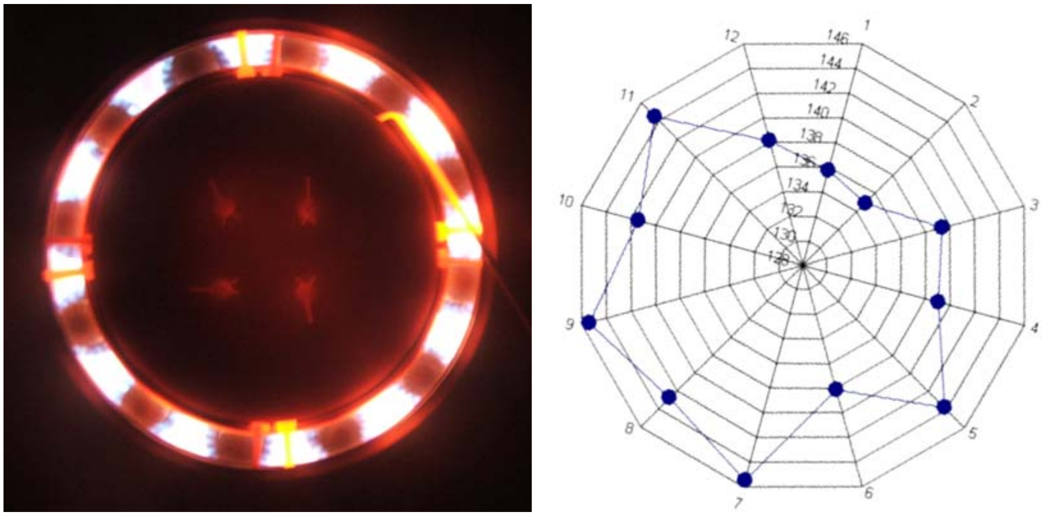



Figure 2. Ignition on 100% Pilot

### 3.2.2 0% Load Results

Pilot stability up to the 0% load (idle) condition was assessed after successfully achieving system ignition. Operating conditions simulating 0% load were reached while maintaining the pilots active with flame temperatures ranging between 2200° and 2400° F. At the 0% load condition, lean extinction assessments showed that the pilots remained stable down to a flame temperature of about 1100°F. This condition is well below the required minimum threshold of stability at a flame temperature of 2200°F. Some variation among pilot flame structures was observed and is shown in Figure 3a.  Brighter reactions generally corresponded to pilots that admitted slightly more fuel as predicted by the cold flow results discussed above.  Figure 3b illustrates the expected air to fuel ratio variation between pilots.




a) Image of Reaction Structure          b) Air to Pilot Fuel Ratio Distribution

Figure 3. 100% Pilot Operation at Simulated 0% Load

While not ideal, the lack of homogeneity in pilot flame temperatures will not be detrimental to the evaluation of this first prototype system.  Operation at maximum pilot flow, required only during transient engine operation, will be maintained to a minimum to minimize stress on engine hot gas-path components.

### 3.2.3    50% Load Test Results

At simulated 50% load and 100% pilot operation, reaction structure distribution remained similar to that found in the 0% load evaluation.  Pilot stability was also excellent, and no issues maintaining the required minimum 2200°F flame temperature were noted.

Temperatures at the exit plane of the combustor were characterized with the use of thermocouple rakes.  The results are presented in Figure 4 for 50% load.  Cold (blue) zones observed correspond to the location of unfired (main) burners for this condition where all fuel was injected through the pilots.  The temperature pattern agrees well with the fuel-air injection variations expected and discussed above.

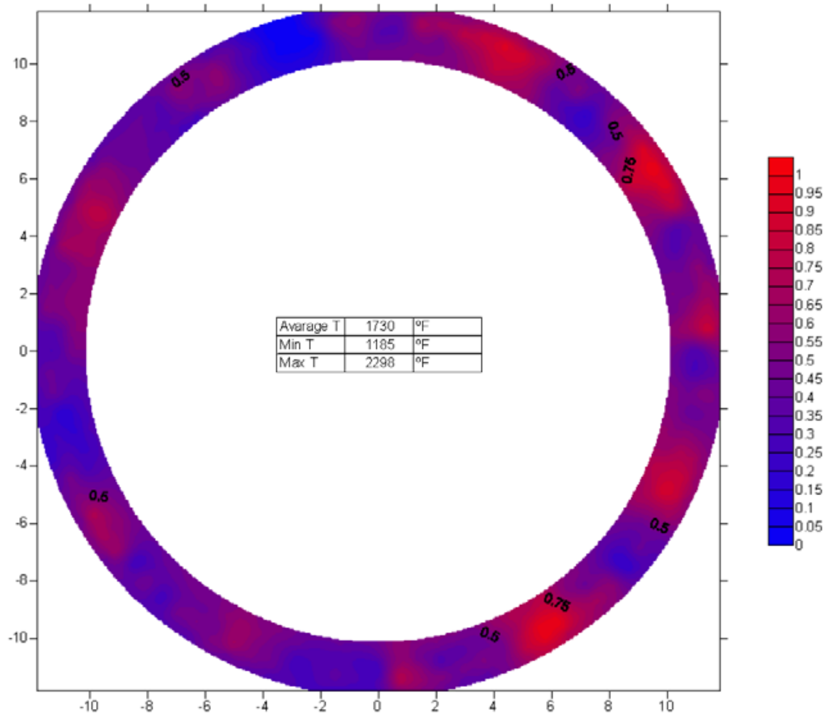



Figure 4. 100% Pilot Operation at Simulated 50% Load: Combustor Exit Temperature Distribution

At 50% load, fuel was transitioned to the main burners and emissions and combustor exit temperatures were characterized at steady state. Figure 5 shows the results of tests conducted to characterize emissions and lean stability versus flame temperature. $NO_x$ levels down to 2 ppm (corrected to 15% oxygen) were recorded at a flame temperature of approximately 2600° F. CO emissions were essentially constant at 4 ppm (corrected to 15% oxygen).

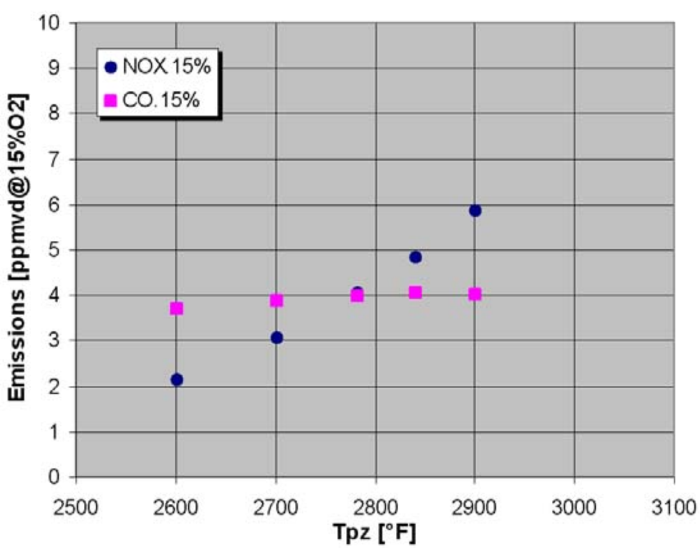



Figure 5. 100% Main Operation at Simulated 50% Load: Emissions as a Function of Flame Temperature

With the flame temperature constant (at 2739°F), the concentration of fuel in each burner was sampled and analyzed. This information is useful in assessing discrepancies with anticipated distribution based on (cold flow) effective area data. Differences are attributed to poor air and/or fuel supply distribution. Samples were extracted via multi-port probes installed in each of the burners and analyzed in a Rosemount NDIR hydrocarbon analyzer. The results obtained enabled the computation of the average flame temperature at each burner. Figure 6 shows a spread of about 119°F (+/- 60 F) between the coldest and the hottest burners. The spread observed is of the same magnitude anticipated based on the cold flow results, however, the locations of the hot and cold zones are not entirely as expected (compare Figure 6 to Figure 7b).

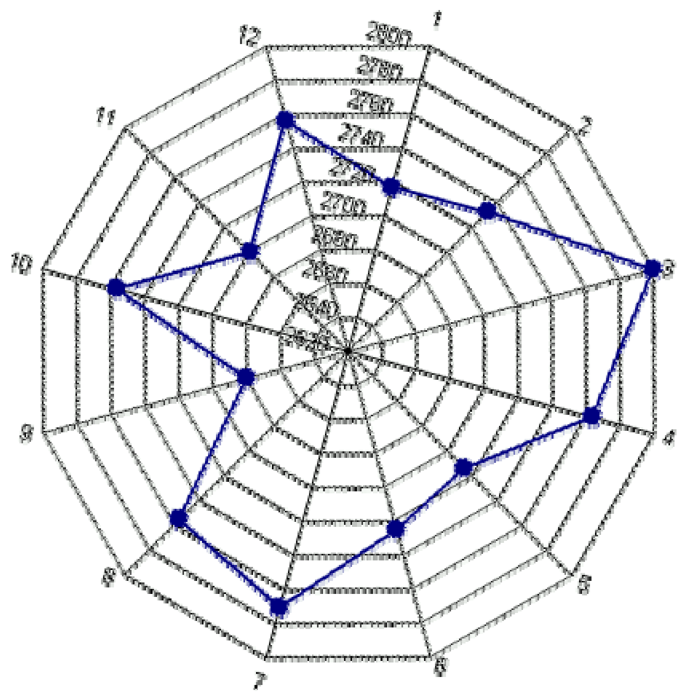
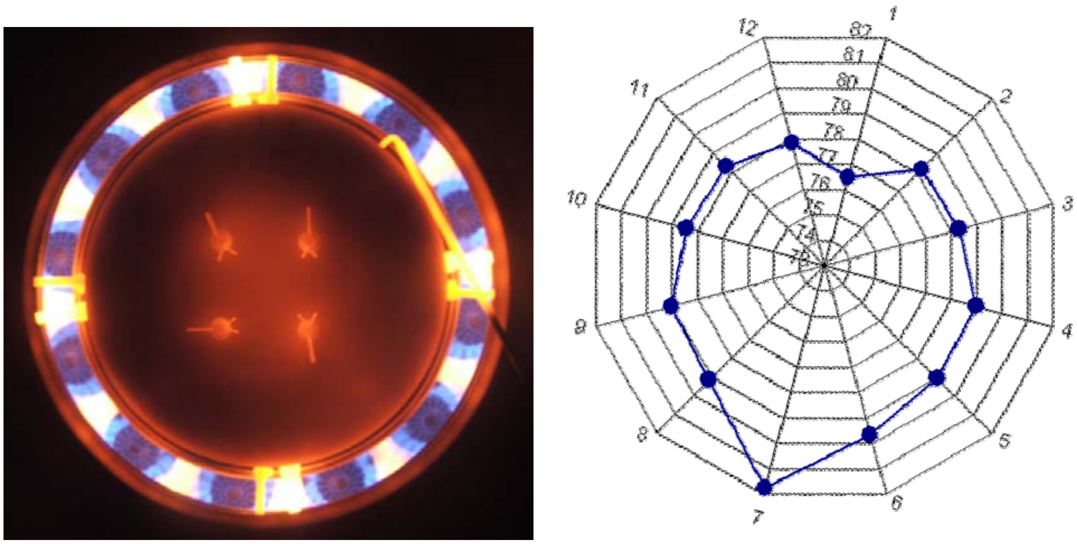



Figure 6. Flame Temperature by Burner: Average= 2739°F; Spread = 119°F

The reaction structure distribution and expected air-fuel ratio variations (from cold flow results) are compared in Figure 7. Visual examination of the level of reaction intensity variation burner-to-burner is not precise enough to allow correlation with the estimated reaction temperature shown in Figure 6.




a) Image of Reaction Structure b) Air to Main Fuel Ratio Distribution

Figure 7. 100% Main Operation at Simulated 0% Load

Metal temperatures of the combustor and the pilots were measured at various locations. On the combustor walls, thermocouples were located at planes located at four axial locations spaced apart by 1.25" starting from the combustor dome (see Figure 8). All temperatures registered at simulated 50% load conditions remained well within acceptable limits for Hastelloy X metal (See Table 3).

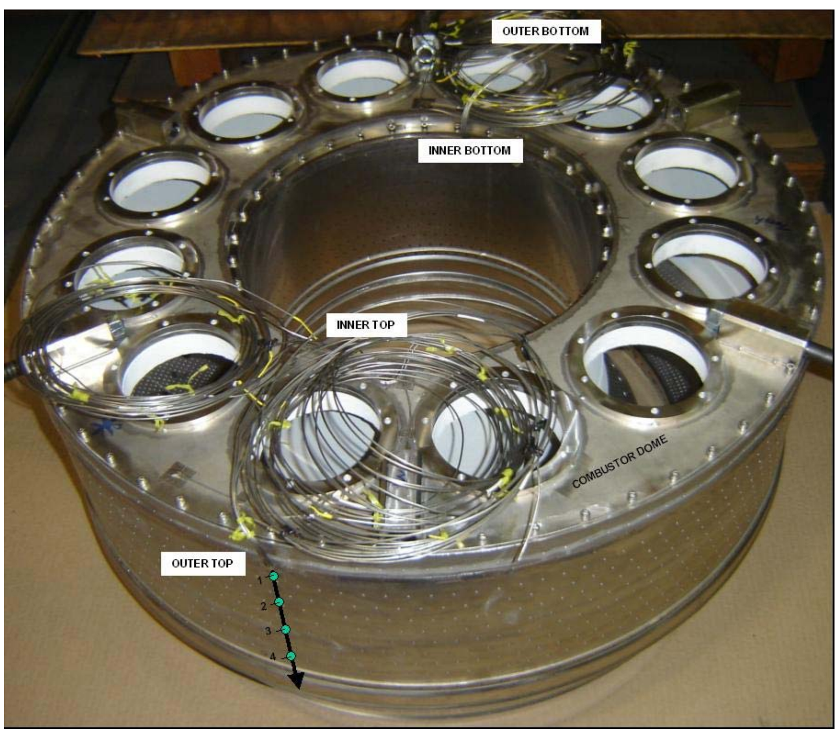



Figure 8. Illustration of TC Locations on Combustor

Table 3. Combustor Wall, Dome, & Pilot Metal Temperatures: 50% Load Averages

Average Temperatures [°F]: 100% Main

| Location | Outer Top | Outer Bottom | Inner Top | Inner Bottom | D Outer Top | D Outer Bott | D Inner Top | D Inner Bott | Pilot |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1092 | 1037 | 1013 | 929 | 709 | 700 | 731 | ~~5565~~ | 910 |
| 2 | 924 | 1103 | 1042 | 1124 | | | | | 1075 |
| 3 | 1138 | 789 | ~~100~~ | 997 | | | | | 923 |
| 4 | 1165 | 470 | 893 | 990 | | | | | |

Average Temperatures [°F]: 100% Pilot

| Location | Outer Top | Outer Bottom | Inner Top | Inner Bottom | D Outer Top | D Outer Bott | D Inner Top | D Inner Bott | Pilot |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 942 | 1124 | 1303 | 1026 | 672 | 678 | 699 | ~~5565~~ | 799 |
| 2 | 902 | 1257 | 1393 | 1255 | | | | | 896 |
| 3 | 1585 | 794 | ~~98~~ | 947 | | | | | 805 |
| 4 | 903 | 505 | 923 | 931 | | | | | |

Values from thermocouples damaged during hardware installation and registering inaccurate readings are crossed out.

### 3.2.4 75% Load Test

At simulated 75% load conditions combustor performance was similar to that observed at 50% load. Emissions are shown in Figure 9. Again, $NO_x$ emissions levels approached 2 ppm at a flame temperature of about 2600°F. At the design flame temperature of 2750° F both $NO_x$ and CO were 3.5 ppm. CO levels remained constant at about 3.5 ppm.

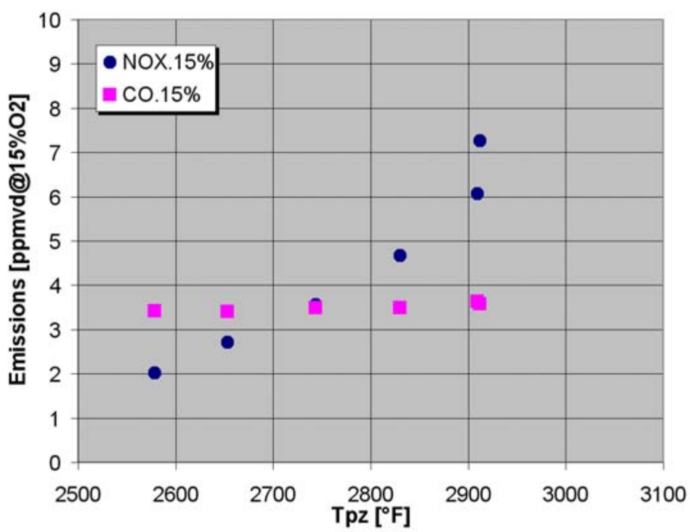



Figure 9. 100% Main Operation at Simulated 75% Load: Emissions as a Function of Flame Temperature

### 3.2.5 100% Load Test

Emissions, combustor exit temperatures, and component metal temperatures were characterized at simulated 100% load conditions. Figure 10 shows the results of a test completed to characterize emissions and lean stability at a nominal (design) operating velocity of 15.6 ft/sec. $NO_x$ levels continued to be primarily a function of flame temperature, with levels approaching 2 ppm near 2600°F. CO emissions remained flat at about 3 ppm.

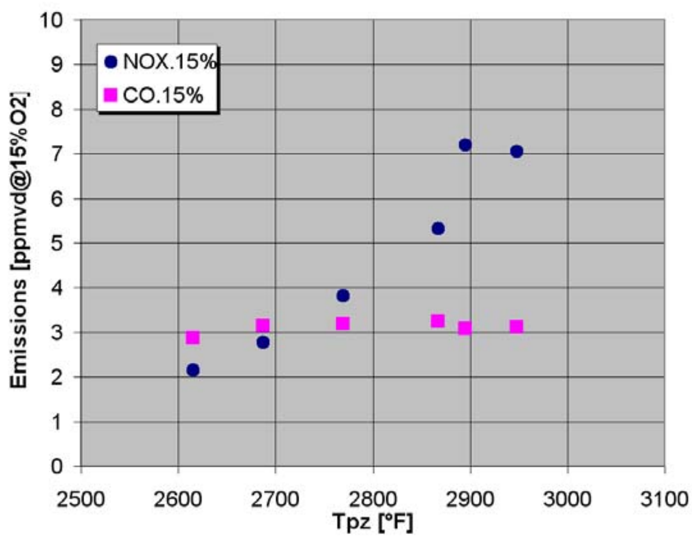
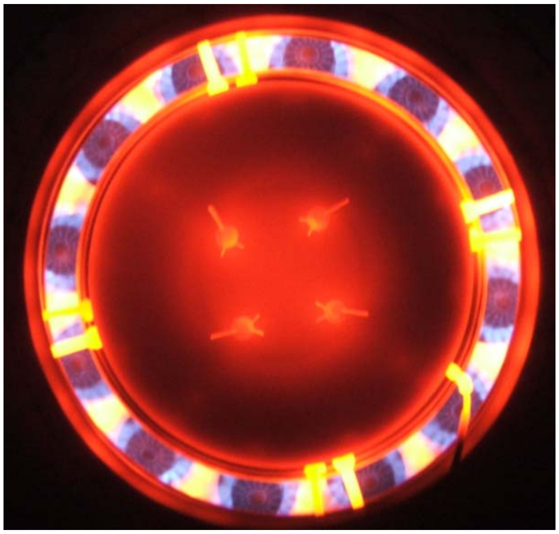
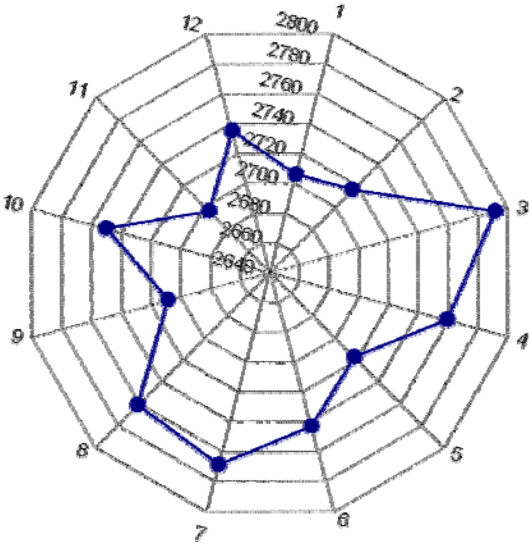



Figure 10. 100% Main Operation at Simulated 100% Load: Emissions as a Function of Flame Temperature

Following the same process described for 50% load conditions, the variation in operating stoichiometry among the burners was quantified by measuring fuel concentration in each burner (at an average overall flame temperature of 2738°F). Flame temperatures calculated from the fuel concentrations are plotted in Figure 11b. Burners 3, 7, and 4 continued to be the hottest, while the 11 and 9 remained the coldest. The spread between the hottest and coldest burner dropped to 95°F (compared to 119°F observed at 50% load). As shown in Figure 11a, this temperature difference could not be visually distinguished.






a) Image of Reaction Structure b) Flame Temperature by Burner

Figure 11. 100% Main Operation at Simulated 100% Load

Combustor exit temperatures were characterized using thermocouple rakes for compliance with the Taurus 70 exit temperature engine specifications. The average radial profile measured is shown in Figure 12 along with the maximum profile specification. A satisfactory profile was documented. A contour plot of the temperatures is shown in Figure 13. The combustor pattern factor was measured at 0.23 which meets the T-70 specification (< 0.25). One change to the combustor dilution zone was required to obtain the results shown.

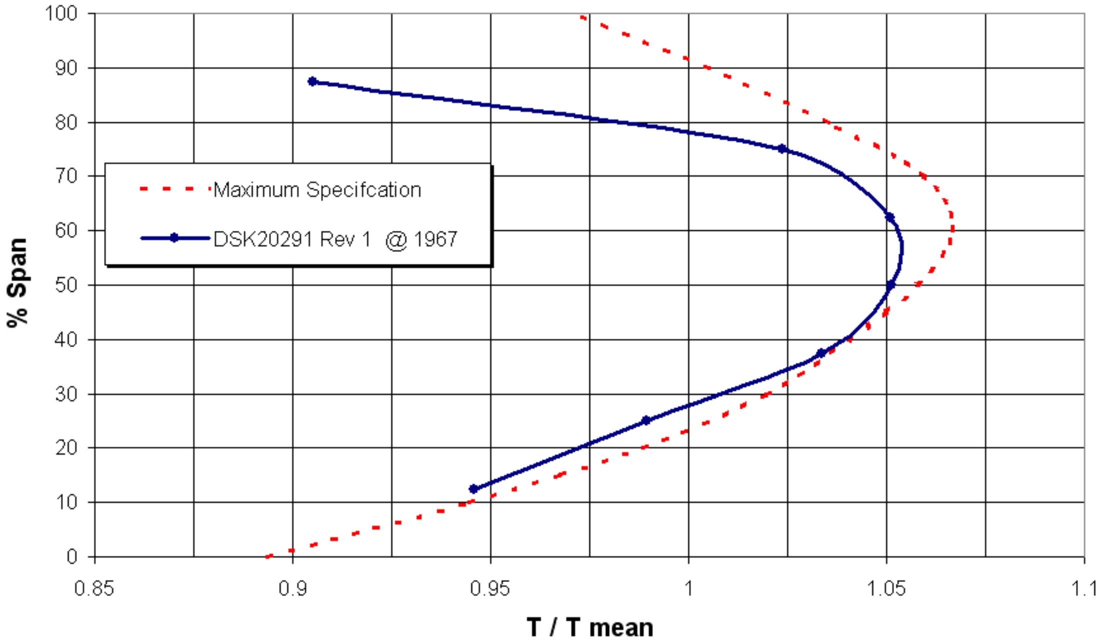



Figure 12. Combustor Exit Temperature Radial Profile: 100% Load Simulation

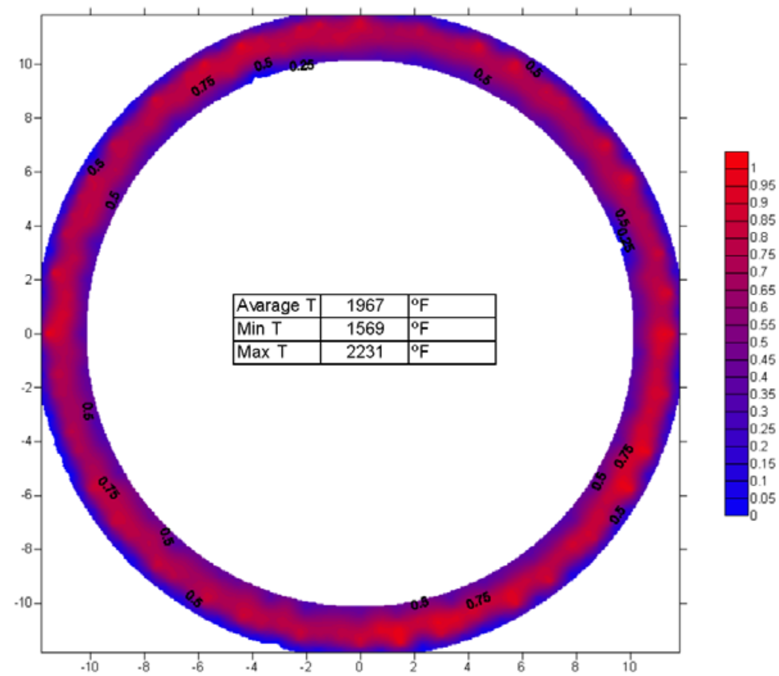



Figure 13. Combustor Exit Temperature Distribution: 100% Load Simulation

Combustor and burner metal temperatures remained well within acceptable limits (< 1600° F). The dome temperatures were only 60°F higher than the inlet air temperature. The highest combustor temperature measured was only 1251°F (see Table 4). The low temperatures measured eliminated the need to conduct additional thermal paint tests. Thermocouples will continue to be utilized in the engine tests planned.

Table 4. Combustor Wall, Dome, & Pilot Metal Temperatures: 100% Load Averages

Average Temperatures: 100% Load T 100% Main

| Location | Outer Top | Outer Bottom | Inner Top | Inner Bottom | D Outer Top | D Outer Bott | D Inner Top | D Inner Bott | Pilot |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1182 | 1131 | 1119 | 1037 | 842 | 829 | 865 | ~~-5565~~ | 1029 |
| 2 | 1040 | 1198 | 1146 | 1223 | | | | | 1162 |
| 3 | 1220 | 916 | ~~104~~ | 1109 | | | | | 1025 |
| 4 | 1251 | 527 | 1014 | 1099 | | | | | |

To explore performance sensitivity of the combustion system, tests were also conducted at combustor air flow rates higher and lower than the design point. The tests provided information on the impact of burner exit velocity and combustor residence time on emissions and combustion stability. These tests were motivated by the possibility that the volume of the burners might significantly reduce the time available in the combustor for CO oxidation to $CO_2$. Higher CO emissions would result. Emissions data from these tests are shown in Figure 14.

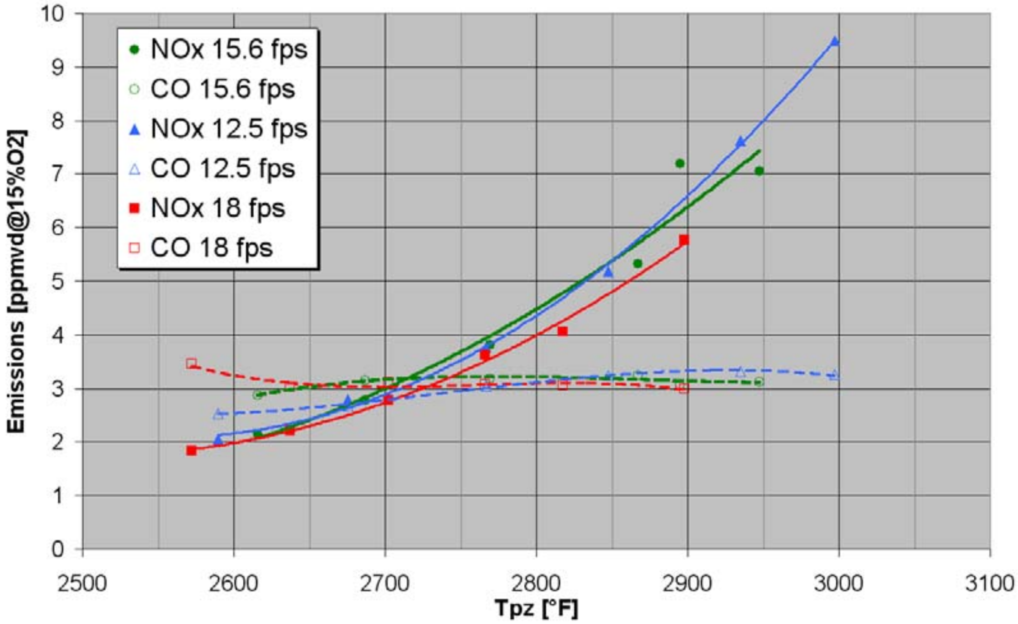



Figure 14. Impact of Residence Time on Emissions: 100% Load Simulation

CO emissions were essentially unaffected by lower flame temperatures and lower residence times (higher burner exit velocity ). There was no indication of inadequate combustor volume for complete combustion. $NO_x$ emissions differences for the three velocities characterized were within anticipated measurement scatter.

### 3.3 Summary

Full-scale atmospheric combustion tests have been completed to evaluate ignition, light-around, flame stability, pilot-to-main transition, combustor exit temperature distribution, emissions, and component metal temperatures. All critical criteria for these parameters have been met successfully.

## 4.0 Future Activities

Mechanical resonance (modal) tests are planned prior to evaluating the T-70 surface-stabilized combustion system on an engine. These tests will seek to determine if any of the combustion system components share resonant modes with the engine first and second order modes (253 Hz and 507 Hz). Work is also ongoing to prepare the engine control algorithms. Pending engine availability, engine evaluations should be completed in November 2006 on a development two-shaft T-70 engine at Solar Turbines.

## 8.10. Appendix II-D: Engine Testing

# Engineering Research and Development Report

# T-70 Engine Test Report

## Catalytic Combustor-Fired Industrial Gas Turbine

## CEC Contract: 500-01-045

## Task 2.5.1

**Issued:** June 25, 2007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**Solar Ref:** S.O. 6-6206-7

## 1.0 Introduction

An initial test of Alzeta's nanoSTAR™ combustion technology has been completed with encouraging results using a natural gas-fired, Taurus 70 engine at Solar Turbines. Smooth engine light-off and acceleration to 50% load were demonstrated repeatedly. Measurements of combustor metal temperatures, dynamic pressure fluctuations, and combustor exit temperature uniformity all met the established engine specifications. Emissions performance at 50% load fell short of the project goals; $NO_x$ was measured at 13 to 15 ppm (@ 15% $O_2$). Testing at higher loads was not possible due a suspected (but unproven) internal air leak within the engine.

Subsequent evaluations suggest two factors that will need to be addressed to achieve the program emissions goals. First, several of the burners may have been operating at higher flame temperatures than desired. This could result from unequal fuel or air flows entering each of the twelve fuel/air premixers used in the combustion system. Second the possibility of a non-uniform inlet air distribution across any one premixer exists. This would degrade the level of fuel/air uniformity at the burner surface and contribute to higher $NO_x$ emissions. The first issue was addressed with in-situ adjustments to the individual fuel metering orifices in each burner. Improving the airflow uniformity at the inlet of mixers is being addressed, and improvements will be evaluated in further rig and engine testing.

Overall, the first T-70 test was deemed a success as transient operation of the combustion system was demonstrated, and a post-test inspection of the combustion hardware showed all the components to be in good condition.

## 2.0 Test Objectives

In-house T-70 engine tests were conducted with a prototype nanoSTAR™ combustion system to evaluate steady state emissions, short-term durability, and system stability during transient engine operation. Specifically, the tests sought to demonstrate:

- smooth and repeatable ignition using the pilot fuel injection system
- a smooth and repeatable transition from the pilot burners to the main low-emissions burners at 50% load
- stable operation on the main burners from 50 to 100% load
- a smooth and repeatable transition from main fueling back to pilot fueling when switching out of the low-emissions mode
- ultra-low emissions between 50 and 100 % load (< 5 ppm $NO_x$ and < 10 ppm CO @15% $O_2$).

Combustor performance data collected included: emissions, combustor dynamic pressure fluctuations, combustor pressure drop, combustor metal temperatures, combustor exit temperature, and the fuel concentration uniformity of the burner set.

## 3.0 Test Results

The results of the engine test are summarized in this section.

### 3.1 Start and Acceleration

At the outset, several attempts were necessary to start the T-70 engine (combustor ignition), smoothly accelerate to the steady state idle condition, and then add load. Several modifications to the engine control logic were necessary to reach 50% load operation in the low $NO_x$ operating mode. After appropriate air bleed and fueling schedules (pilot and main) were established, the start/load cycle was demonstrated to be robust and repeatable.

Figure 1 shows time traces of several critical operating parameters during a typical start cycle. Following a standard engine air purge (starter cranked with no combustion), ignition of the nanoSTAR™ pilot burners was accomplished with a modified T-70 torch igniter. The engine accelerated to idle smoothly (~ 72% engine speed, Ngp) using standard T-70 control algorithms. Once engine idle was achieved, “bleed valve control” was activated. This control algorithm modulated the flow of bleed air (air bled from the compressor prior to entering the combustion system) in order to maintain the combustor primary zone temperature (Tpz) at a desired set-point. For effective operation of the pilot burners, the set-point was initially fixed at 2200°F. With the bleed control active, the engine was successfully accelerated to 83% Ngp using only the pilot burners.

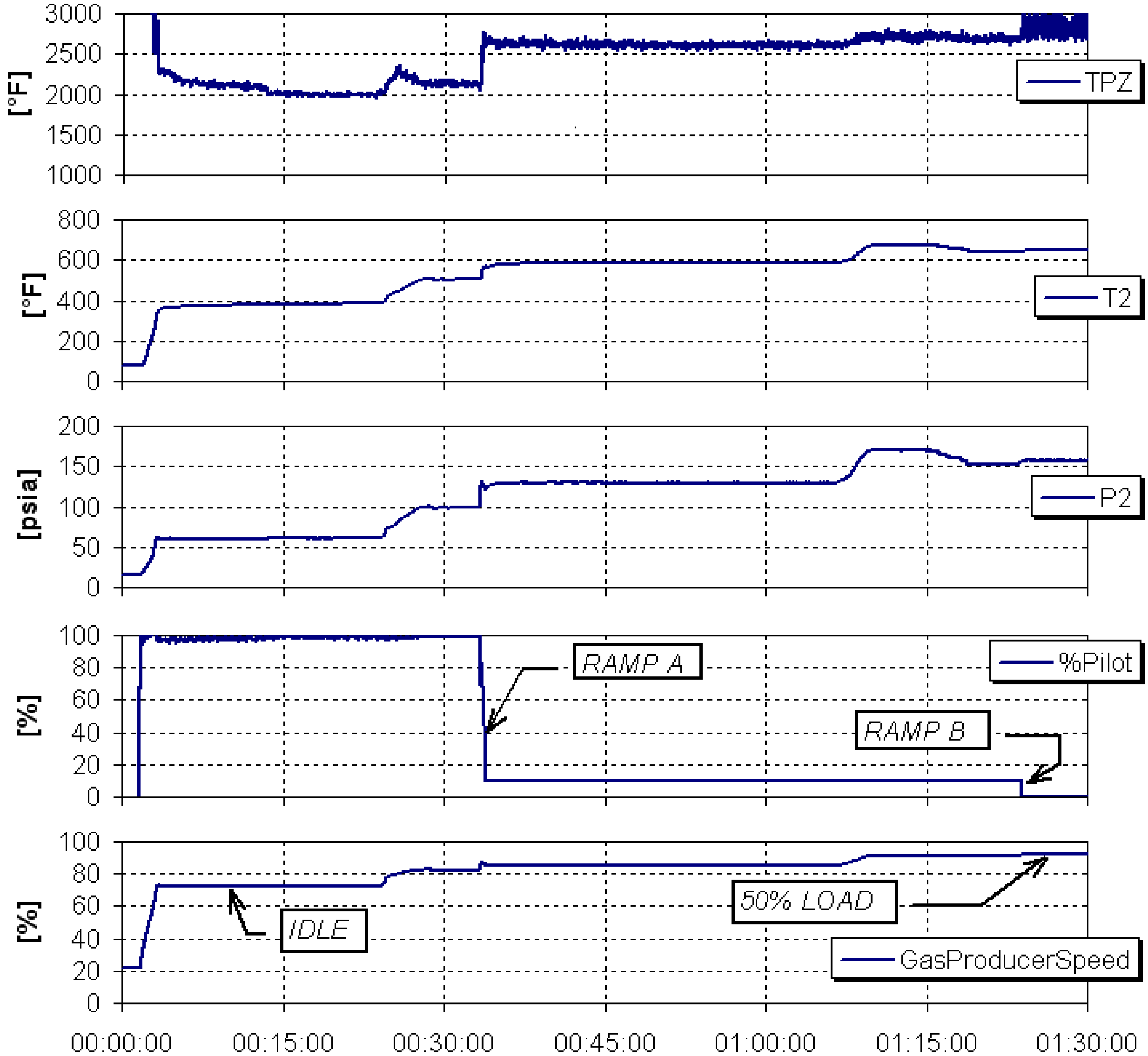


Figure 1. Sample Start Cycle

The transition from pilot burner to main burner (low emissions) operation was accomplished in two phases. The first phase, designated "Ramp A", involved transferring 90% of the total fuel flow from the pilot stage to the main stage. Primary zone temperature was simultaneously increased to 2600°F. Ramp A was executed as a linear ramp with a duration of 30 seconds.

With fuel flow to the main stage enabled, an initial assessment of injector-to-injector premix uniformity was performed. Using a direct sampling method, the average fuel concentration inside each of the 12 main injectors was measured. Figure 2 shows the results of this assessment with fuel concentration represented by calculated Tpz. The peak-to-peak flame temperature spread observed, ~ 350 °F, was significantly above the design goal of 200°F. The spread is undesirable from a $NO_x$ emissions perspective; however, it posed no significant risk of damage to the hardware. Consequently, testing proceeded.

Combustor exit temperature uniformity was also evaluated by monitoring the power turbine inlet temperature (T5) distribution.  Twelve thermocouples allowed for real-time monitoring of this profile.  Despite the unusually high fuel concentration spread among injectors, the T5 distribution conformed to the engine specification (Fig. 3).

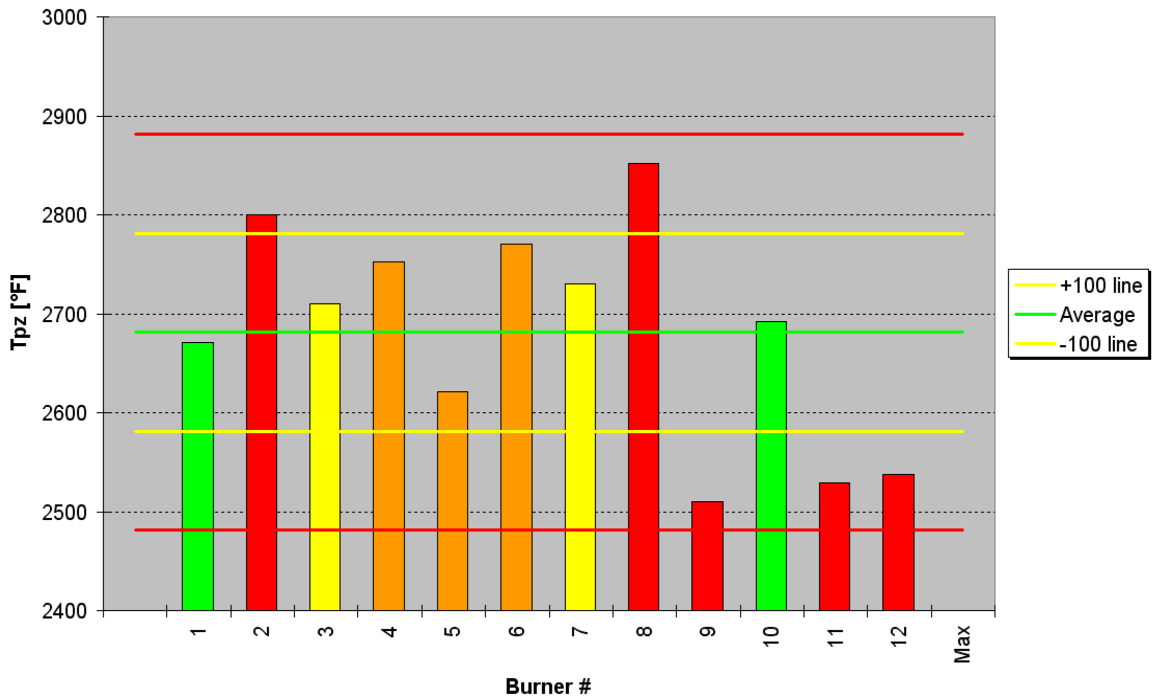



Figure 2:  Injector Premix Survey, 83% Ngp

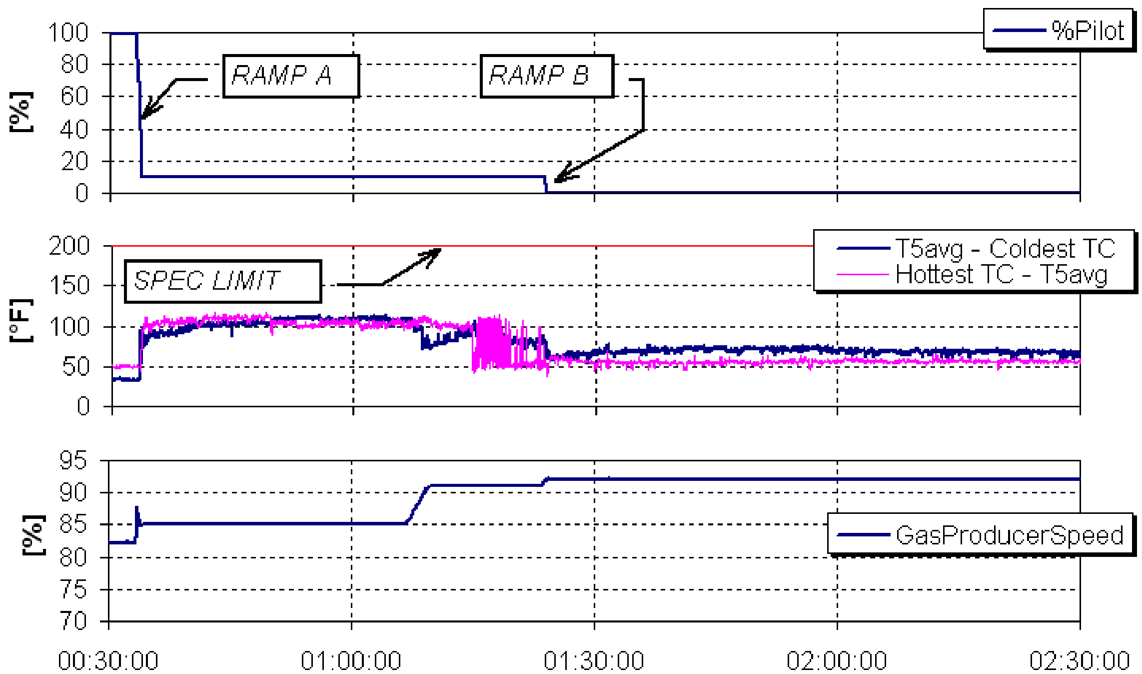



Figure 3. Sample T5 Distribution

After fuel feed and exit temperature uniformity were observed, the remaining 10% of the fuel flow was transferred from the pilot to the main burners. This transition, "Ramp B," took place at a constant engine speed of 92% Ngp. Simultaneously, primary zone temperature was increased to the low-emissions design point of 2750°F. Ramp B was executed as a linear ramp with a 5 second duration. During testing, the pilot flames actually extinguished an instant *before* the design Tpz was reached. Consequently, short-lived, low amplitude, low frequency pressure oscillations (rumble) were encountered. These oscillations disappeared as Tpz reached the set-point for stable main-only operation. The short rumble duration ensured that no hardware damage resulted. In future tests the control scheme will be tuned to avoid rumble during the Ramp B transition.

3.2 Low-Emissions Operation

With all the fuel flow going to the main burners, the combustor was fully operational in its low-emissions mode. A second fuel feed uniformity assessment was conducted at 92% Ngp (~ 50% load). The results of this assessment (Fig. 4) were very similar to those previously attained at 83% Ngp. Thus it was concluded that injector-to-injector fuel uniformity was substantially unaffected by engine operating conditions.

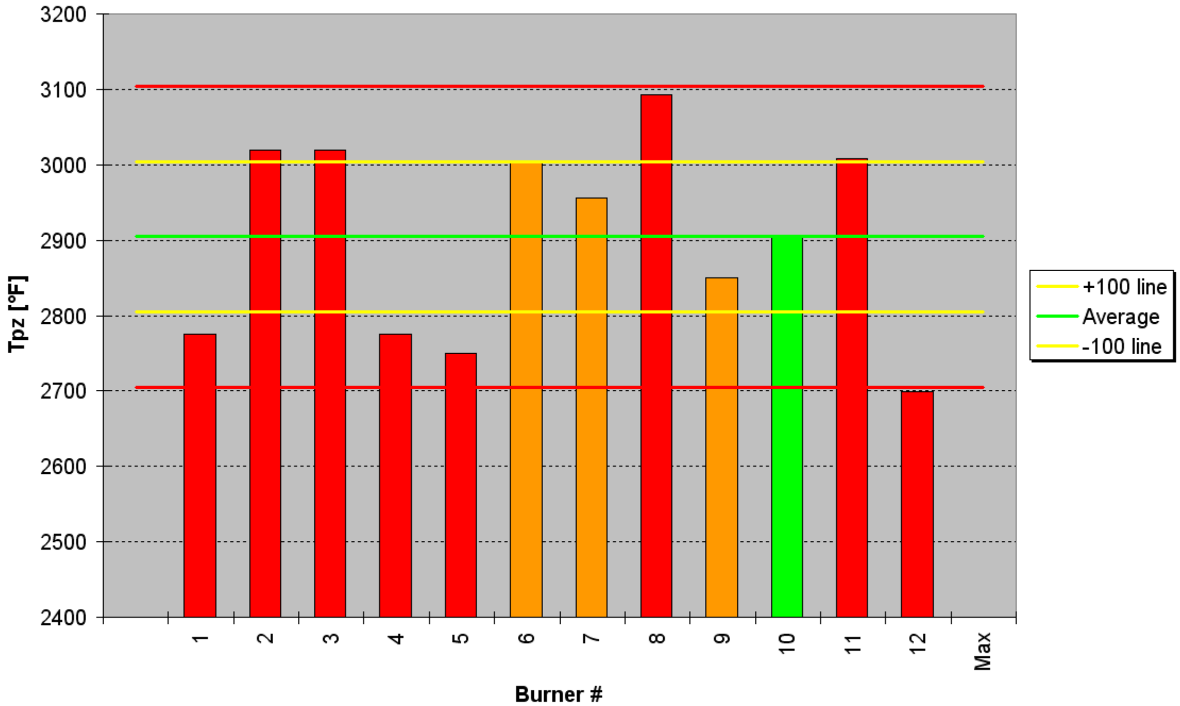



Figure 4: Injector Premix Survey, 92% Ngp

Main burner emissions measurements were also taken at 92% Ngp. At the design flame temperature of 2750°F, $NO_x$ emissions were approximately 15 ppm (corrected to 15% $O_2$). CO and HC emissions were above the measurable scale of the available emissions train (200 ppm CO and 100 ppm HC).

Several critical performance parameters were measured while operating in the low-emissions mode. Combustor metal temperatures were all below design goals indicating acceptable liner cooling. No significant dynamic pressure oscillations were observed while operating in the low-emissions mode. The combustor exit temperature (T5) profile was once again shown to conform to specifications. In terms of these important parameters, the engine test was deemed a success.

During engine operation in the low-emissions mode, it became apparent that the pressure drop across the combustor was lower than expected for the amount of airflow being measured at the engine inlet. Thus the amount of air reaching the injectors was also unusually low. This apparent "air leak" (air bypassing the combustor) limited the ability to control Tpz and also prevented acceleration of the engine beyond 92% Ngp (50% load) without exposing the burners to potentially-damaging high flame temperatures. Thus, the first round of tests was concluded and the engine was shutdown in a controlled manner.

After the first round of low-emissions testing, it was postulated that the sub-par emissions performance could be attributed to the larger-than-expected spread in injector-to-injector fuel concentration. If certain injectors were operating nearly 350°F hotter than others, these hotter injectors would contribute significantly to higher $NO_x$ levels. Since the fuel-air ratio of each injector was tuned prior to installation, any variation in operating flame temperature was likely attributable to factors associated with the injectors after installation in the engine. Specifically, one factor could have been the flexible fuel supply lines used to feed each injector. Since these were custom installed for each injector, a different amount of fuel flow may have been reaching each injector. Using a novel in-situ flow test, these variations were quantified. A new set of fuel orifices was designed and installed to compensate for the fuel variations.

A second engine test was conducted with the new orifices in place. The test allowed an assessment of the impact of a more uniform fuel flow to the injectors on $NO_x$.. As in the prior test, engine start and transition to low-emissions mode occurred smoothly. Once main stage combustion was established, a premix survey was conducted. Results of this assessment are shown in Figure 5. The data show that the injector tuning method was somewhat effective. Peak-to-peak flame temperature spread was reduced to approximately 250°F (about 100 °F lower), nearly meeting the original design goal of 200°F. However, the emissions data did not show a significant improvement. $NO_x$ emissions at 50% load were approximately 13 ppm, while CO and HC emissions remained above the scale of the available instruments. Since the internal air leak prevented testing at higher loads, the engine test was concluded.

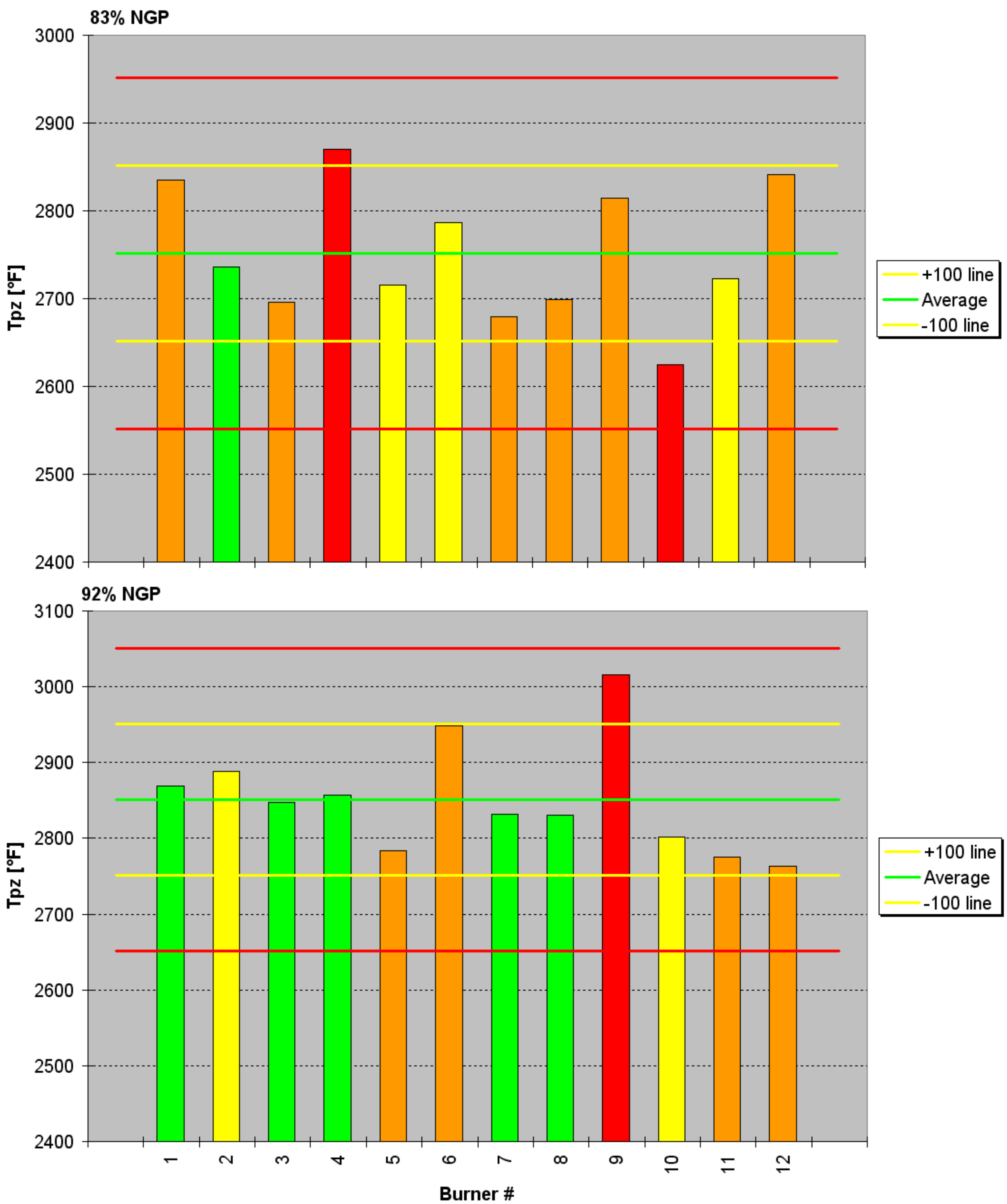


Figure 5: Injector Premix Surveys after Orifices were Installed

## 3.3 Additional Diagnostics

It had been suspected that the emissions performance shortcomings described above were likely attributable to one (or both) of two major factors. The first factor, described above, was poor distribution of fuel to each of the twelve premixer/burner assemblies. The second factor was poor premixing performance within any one (or more) of the injectors. It was recognized prior to engine testing, that the airflow patterns upstream of the combustor would be different in an engine than in the test rigs used for initial burner development. It was possible that the aerodynamics of the engine compressor/diffuser (upstream of the combustor) could create a biased flow across the inlet face of the premixers. This would degrade overall premixer performance and contribute to higher $NO_x$.

CFD analyses supported this suspicion as depicted in Fig. 6. Figure 6 illustrates the jet trajectory from the diffuser (flow from right to left) and how the jet may impinge directly on the lower section of the premixer inlet face. Such a bias could result in poor fuel/air mixture uniformity within each injector. Subsequent single-injector tests confirmed that non-uniform premixing could have a detrimental impact on emissions.

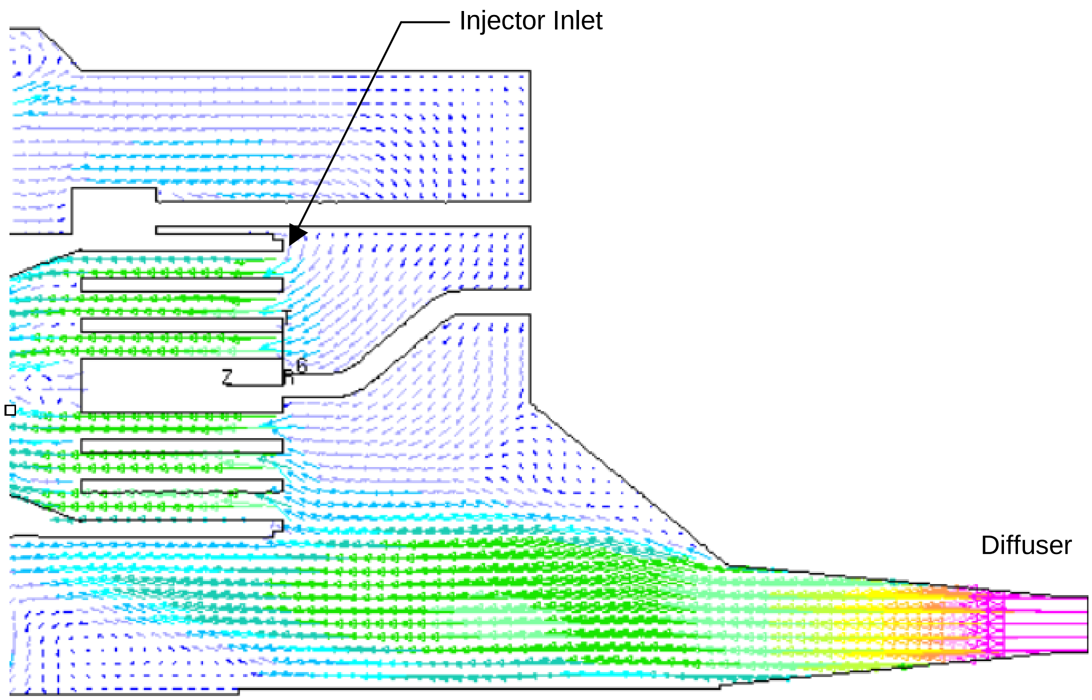



Figure 6. CFD Analysis of the Air Flow-field Entering Injectors in an Engine Setup

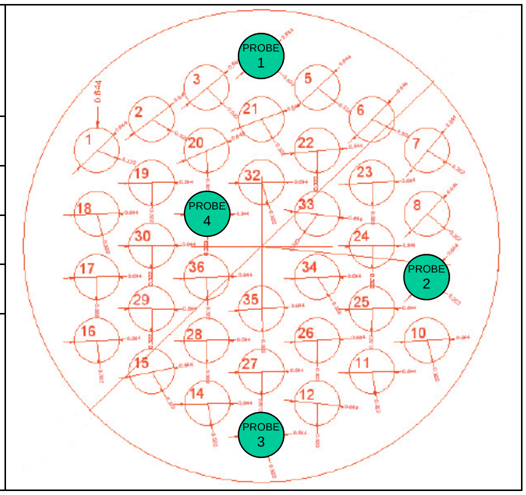
It should be noted that the accuracy of the premixer inlet flow CFD calculations (as typified in Fig. 6) are largely unknown. The calculations showed that the flow field upstream of the combustor was very sensitive to the assumed inlet velocity profile of the diffuser. Extremely limited diffuser inlet flow data are available to support the CFD calculations.

In order to quantify the level of fuel/air unmixedness occurring during the engine test, a novel measurement technique was developed. One burner of the engine set was instrumented with four individual premix sample probes. Each probe consisted of a 1/16” diameter tube inserted through one of the premixing tubes. The probes extracted a fuel/air sample from approximately ¼” downstream of the exit of the mixing tube. The four mixing tubes that were instrumented were selected to provide a broad spatial profile – three were spread around the circumference of the mixer and one was located near the centerline (see Table 1). With the engine running at crank speed, a small amount of fuel was introduced to the instrumented burner and fuel concentration measurements were made for each of the four tubes. This test allowed an assessment of the uniformity of the mixture within a single burner, and, indirectly, the uniformity of the airflow field within the engine.

Table 1 shows the data collected from each of the four local sampling probes, as well as the average fuel concentration measured with the burner averaging-probe installed further downstream.

Table 1. Quantification of Spatial Unmixedness in Injector # 2

| Probe | Measured Fuel Concentration (and Tpz, °F) |
|---|---|
| 1 | 5.11% (2797) |
| 2 | 3.81% (2338) |
| 3 | 3.20% (2112) |
| 4 | 3.96% (2392) |
| ***Averaging Probe*** | 4.26% (2500) |




The fuel concentration measured by probe #1 was 20% above the averaging probe, while probe #3 indicated a concentration 25% below the averaging probe. Extrapolated to full-load design conditions, this non-uniformity would result in a peak-to-peak flame temperature spread of approximately 800°F. Thus the data from this test support the idea that inlet flow non-uniformities are affecting the engine test results. It appears very likely that a significant airflow bias exists within the engine, leading to a significant impact on flame structure of the burner (as simulated subsequently in single injector tests and shown in Figure 7) and a detrimental impact on emissions.

To improve performance in a second engine test, methods have been assessed to provide a more uniform flow into the premixers. The preferred approach is through the use of a number of grids mounted on the injector inlet faces that will better distribute the flow (at the expense of somewhat higher burner pressure drop).

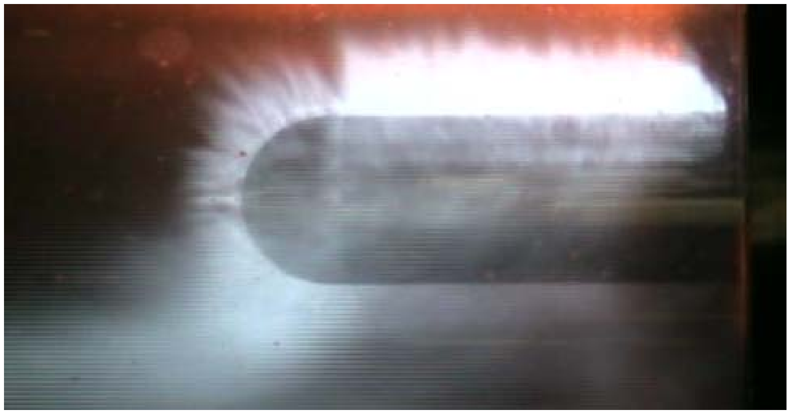


Figure 7. Simulated Impact of Biased Air Flow on Burner Flame Structure

A second factor requiring assessment was the internal engine air leak suspected during the engine test. At times during the test, up to 15% of the engine airflow was unaccounted for (based on pressure drop measurements). Technicians conducted inspections while the engine was at idle speed and found only minor air leaks to the test cell though flanged joints. Therefore a significant air leakage around the combustor was thought to exist somewhere inside the engine. It has long been known that intrusion of cold air into the primary zone can have a detrimental effect on nanoSTAR™ emissions. Potential primary zone leak paths include: leaks through the torch port, through the injector mounting flanges, or through the combustor dome flange. Other downstream leak paths might include the fishmouth interface at the combustor exit or the turbine nozzle seals.

After the combustor was removed from the engine, all of these potential leak paths were investigated. Visual inspection of the combustor confirmed that no major hardware damage had occurred. All engine components appeared to be properly installed. There were no telltale signs of primary zone leakage such as loose bolts, missing gaskets, or erosion of the combustor dome insulation material. Flow tests of the combustor and first-stage turbine nozzle yielded the expected values. Fishmouth engagement was verified with CMM measurements and by carefully comparing component drawings to the corresponding production parts. At this time, therefore, the source of the air leak remains unknown. However, it is likely that the leak was unique to that particular engine build, and future engine tests with the current combustor are planned.

## 4.0 Conclusions and Future Activities

The T-70 engine test represents the first time that a nanoSTAR™ surface-stabilized combustion system has been integrated into an industrial gas turbine in a multi-injector annular configuration. Ignition with the pilot burners was smooth and reliable. Transfer of fuel flow from the pilot stage to the main stage was accomplished using a two-part control sequence. The engine maintained stable operation at speeds up to 92% Ngp and loads up to 50%. $NO_x$ emissions were shown to be less than 15 ppm, but CO and HC emissions were high. The engine was successfully shut down after each test run with no detrimental effects observed.

The high $NO_x$ and CO emissions were attributed to poor premixer performance resulting from poor air distribution at the inlet of injectors. Initial measurements were made to verify and quantify the problem. Future engine tests will seek to address mixture quality by establishing a uniform airflow field at the inlet of the injectors. Potential solutions will be first evaluated in subscale rigs, then in a full-scale high-pressure facility, and finally demonstrated in further engine tests.

## 8.11. Appendix II-E: Loop Engine Testing

# Engineering Research and Development Report

# Loop Engine Test Report

## Catalytic Combustor-Fired Industrial Gas Turbine

## CEC Contract: 500-01-045

## Task 2.5

**Issued:** October 12, 2007

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**Solar Ref:** S.O. 6-6206-7

**Nomenclature**

| | |
|---|---|
| Ae | Effective area |
| AFR | Air-to-fuel ratio by mass |
| Alpha | Percent of total combustion air flowing through burners |

$$\text{Alpha} = \frac{\sum Ae_{burner}}{\sum Ae_{burner} + Ae_{comb}}$$

| | |
|---|---|
| Mixture Velocity | Velocity of fuel-air mixture flowing across the burner surface<br>Q.mixture/Burner.Surface.Area |
| LBO | Lean blowout |
| Loop Engine | Recuperated C-40 engine with silo-style combustor interface |
| Premix | Mixture of fuel and air provided to the burner |
| SN | Serial number |

<u>subscripts</u>

| | |
|---|---|
| burner | burner air side (single burner) |
| comb | combustor liner |
| main | main fuel circuit |
| pilot | pilot fuel circuit |

## 1.0 Introduction

Evaluations of a Taurus 70 (T-70) nanoSTAR™ combustion system have been completed successfully at Solar Turbines. Testing on natural gas was conducted using a modified Centaur 40 (C-40) test engine. The C-40 engine was able to match the full load operating conditions of the T-70 except for combustor pressure (7.5 atm vs. 16 atm).

Two C-40 tests were completed. The first test was conducted with the identical hardware used in a prior T-70 engine test. The second test was conducted with a set of perforated plates mounted on the inlet sections of the fuel/air premixers. In the second test, the premixer inlet plates improved the air distribution and resulted in $NO_x$ emissions below 3 ppm with less than 15 ppm CO (both corrected @ 15% $O_2$). $NO_x$ emissions were approximately 50% higher in the first test where the inlet airflow was not as uniform.

Both tests were characterized by smooth engine startup and acceleration to full-load conditions. At no time were combustor oscillations encountered, which appears to be a major advantage of the nanoSTAR™ system over conventional low $NO_x$ systems.

The test results demonstrated the importance of a uniform air distribution upstream of the combustor in achieving ultra-low emissions. It is now deemed very likely that the unexpectedly high $NO_x$ emissions observed in a prior T-70 engine test were the result of flow non-uniformities that develop as the compressor discharge flow expands into the combustor housing. On-going work will be focused on improving the airflow uniformity within the T-70 engine.

## 2.0 Background

Prior to the C-40 tests described below, a test of the nanoSTAR™ combustion system was conducted using a T-70 engine at Solar Turbines. The T-70 is the target application for this program. The T-70 test resulted in poor emissions performance relative to earlier single injector tests. At that time it was hypothesized that the high emissions were due to a non-uniform air distribution in the combustor plenum. This was supported by subsequent analyses (CFD modeling and single burner tests) that showed that a poor air distribution degraded both premixedness and the flame structure uniformity (Fig. 1). With less effective premixing, high $NO_x$ and CO emissions would be unavoidable (see Topical Report Task 2.5.1).

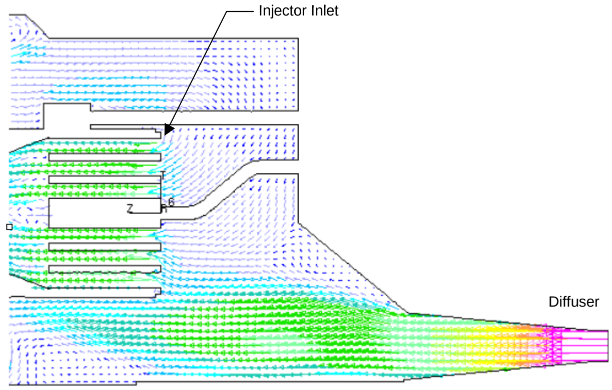


Figure 1A. CFD Flow Analysis Showing Non-Uniform Premixer Inlet Flow Pattern

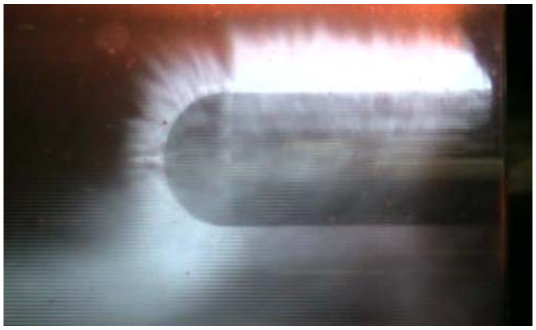

Figure 1B. Single Burner Rig Test Photo Showing Flame Distortion from Forced Flow Biasing

To address the flow uniformity issue more quickly and cost-effectively, combustor testing was shifted from the T-70 engine to the more accessible C-40 engine rig. The test plan included a C-40 test with the same hardware used in the T-70 and then a second C-40 test with the premixer flow uniformity improved.

The C-40 test engine was unique in that it had been reconfigured to operate with an external, side-mounted combustor configuration. The engine is commonly referred to as the “loop” engine because of the unique external ducting required. Testing in the loop engine facility enabled the T-70 nanoSTAR™ combustion system employed in previous in-house engine tests to be run on the smaller C-40 unit. (Figure 2).

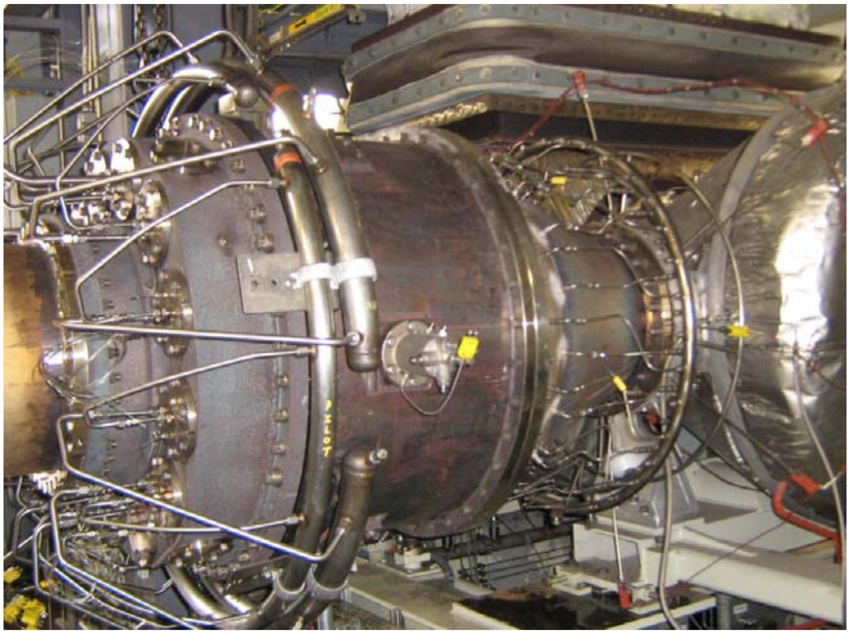

Figure 2. T-70 nanoSTAR™ Combustion System in Loop Facility

Since redesigning the T-70 compressor diffuser or combustor to improve the flow uniformity would be a major effort, the approach adopted was to mount a set of perforated plates on the mixer inlets for the second C-40 test (Fig. 3). The plates reduced the premixer sensitivity to airflow non-uniformities at the expense of increased pressure drop. The perforated plates were designed to restrict the airflow entering the mixers to 64% of the total airflow as compared to 71% without the plates.

The two tests were successfully completed; the first test with no inlet plates and the second with the plates installed.

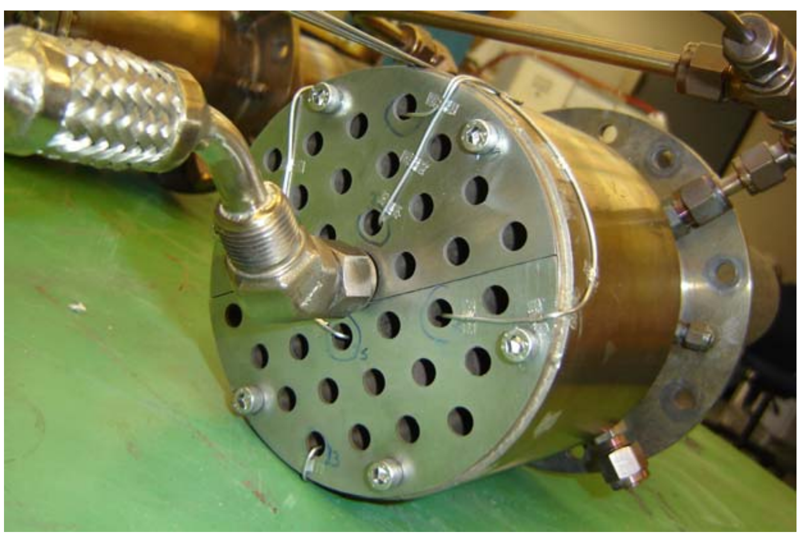

Figure 3. Fuel/Air Premixer with "Restrictor" Plate Installed

## 3.0 Test Objectives

Evaluations in the loop facility involved characterizing performance with and without the fuel/air premixer "restrictor" plates. Once reaching engine full-load, the unique recuperative capability of the facility enabled the combustor inlet temperature to be boosted to T-70 full-load levels. The tests served primarily to characterize emissions and lean stability at maximum engine load.

## 4.0 Test Results

Summaries of the start and acceleration performance, emissions and stability at full load, and premix distribution assessments are presented in this section.

### Start and Acceleration

During the testing, the engine was started and accelerated a number of times. The control logic consisted of steps similar to those developed for the T-70 engine:

1. Ignition on 100% pilot
2. Acceleration up to 90% NGP on 100% pilot
3. Transition to 10% pilot / 90% main at 50% load
4. Acceleration from 50 to 100% load on 90/10% main/pilot
5. Transition to 100% main at 100% load

Smooth light-off, acceleration, and transitions between pilot and main stages enabled maximum engine load attainment without any problems. Operationally, the restrictor plates made no difference. Overall, approximately 16 hours of operation and 7 starts/shutdowns were added to the nanoSTAR™ combustion system without causing any hardware damage or visible degradation.

### Emissions and Stability at Full Load

At full load engine operation, exhaust heat recuperation elevated combustor inlet air temperature from about 550°F to nearly 800°F. This increased the burner exit velocity to about 15 ft/s, matching T-70 full load conditions. Combustor pressure was approximately one-half of the T-70 full load pressure (115 psia vs. 240 psia). Emissions were characterized at these conditions while decreasing flame temperature modestly to quantify lean stability.

Figure 4 presents the CO versus $NO_x$ results for the combustion system with and without restrictors. The presence of the restrictor plates allowed the burners to operate with $NO_x$ emissions below 3 ppm (corrected to 15% $O_2$). In contrast, without the restrictor plates, the lowest $NO_x$ emissions recorded were about 4.3 ppm (corrected to 15% $O_2$).

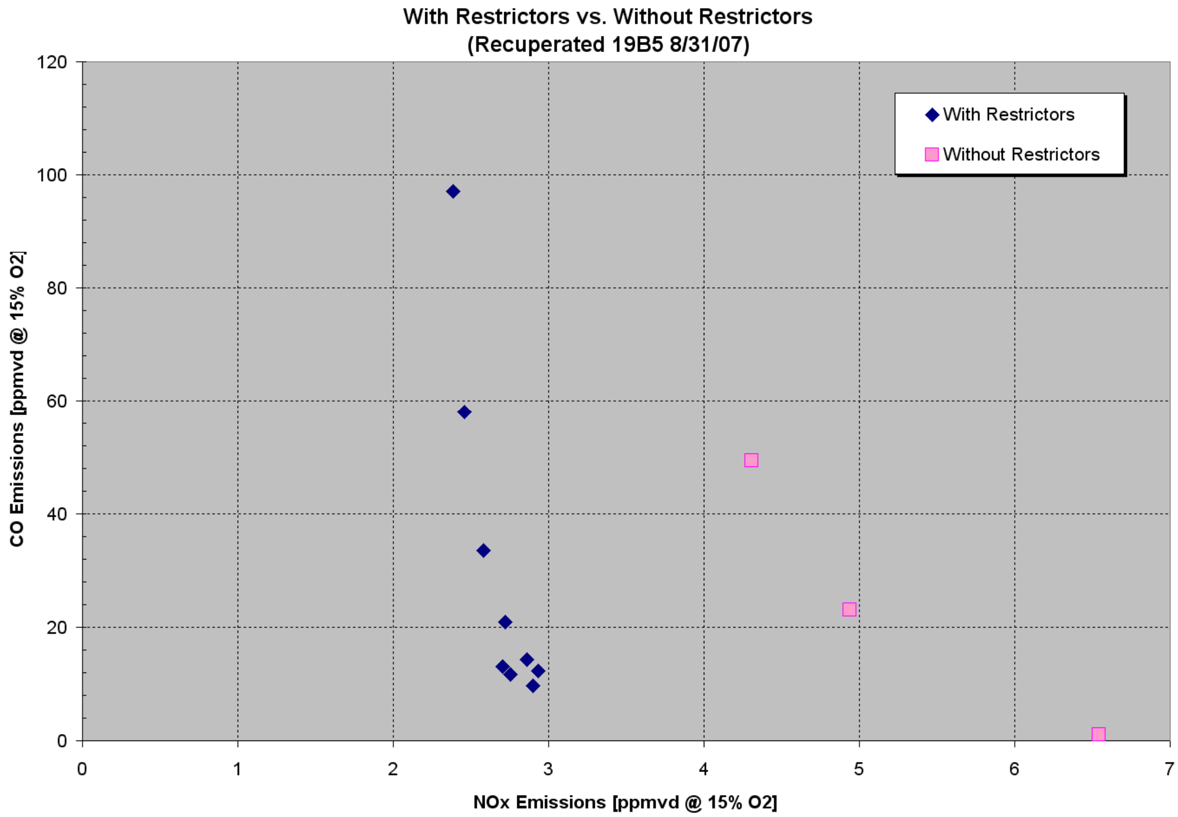


Figure 4. CO vs. $NO_x$ Emissions: With and Without Restrictor Plates

Figure 5 shows the same emissions data plotted versus flame temperature to better illustrate the lean stability characteristics. Numerical values next to the data points indicate the actual inlet air temperature (T2, °F) and the burner mixture velocity (ft/s) corresponding to that data point. Unburned hydrocarbon emissions (HC) are also shown. The rapid rise of HC and CO levels as flame temperature decreases indicates proximity to the lean blowout point (LBO). Performance with the restrictor plates allows the burners to operate with both lower $NO_x$ and CO than without the plates. This is interpreted as indicating the performance degradation attributable to non-uniform premixer inlet flows.

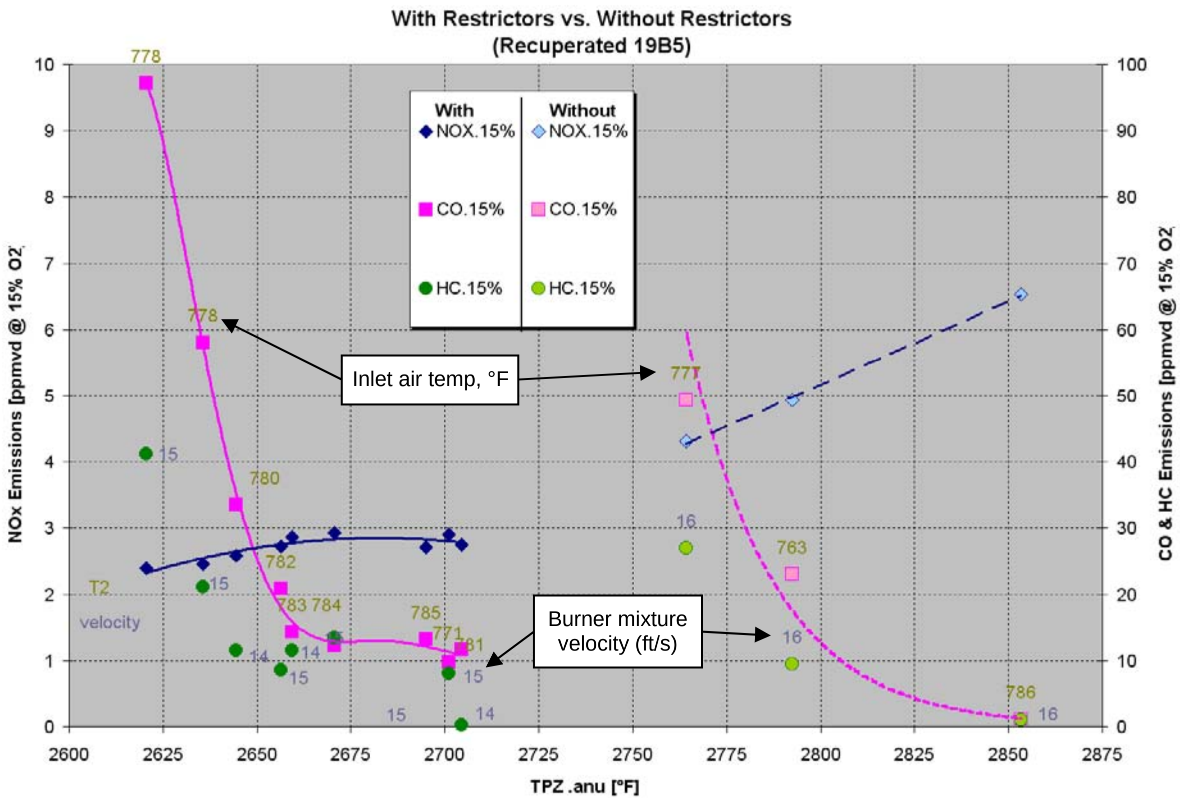


Figure 5. Emissions and Stability: With and Without Restrictor Plates

Dynamic pressure oscillations due to combustion were monitored using a piezoelectric probe mounted to the combustor torch port. No significant pressure oscillations were detected under any of the conditions tested (Fig. 6). In fact, the values recorded, 0.02 to 0.03 psi (rms), are nearly an order-of-magnitude lower than levels typically seen with more conventional low emissions combustion systems.

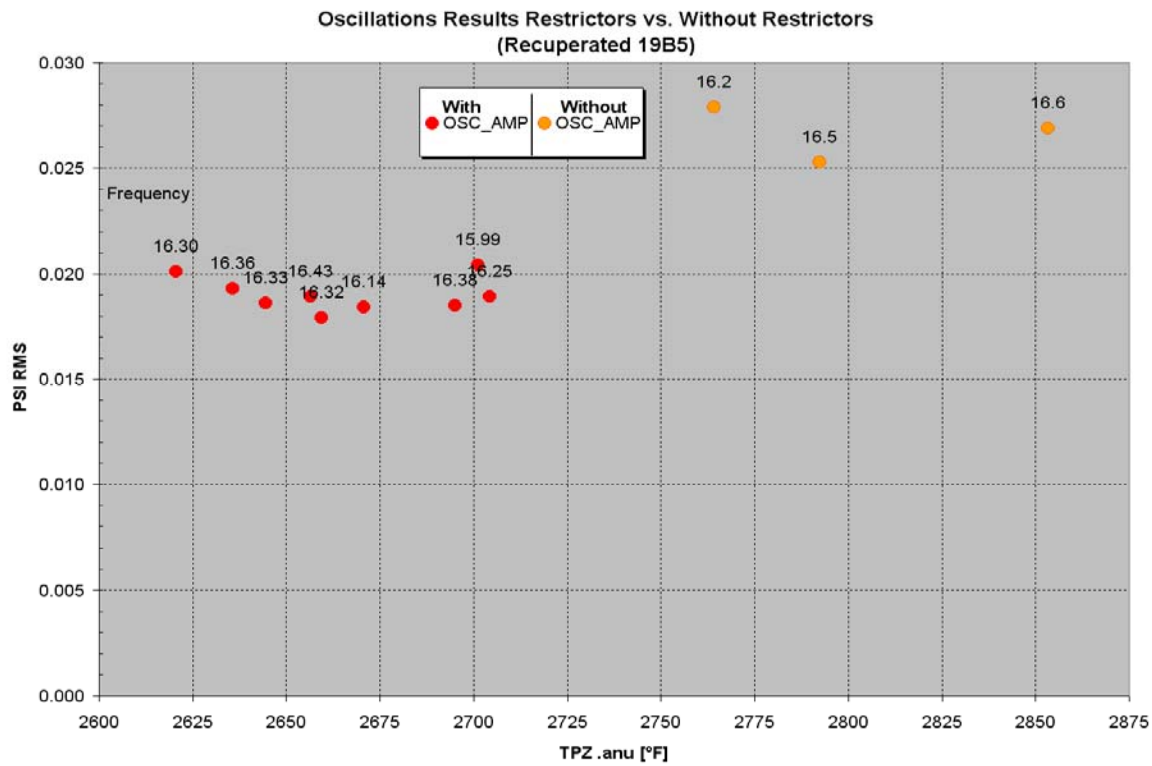


Figure 6. Dynamic Pressure Oscillations: With and Without Restrictor Plates

**Premix Distribution Assessments**

During testing, each of the burners was instrumented with a small gas sampling probe to measure the spatially-averaged fuel concentration just downstream of the premixer exit. Each sample rake consists of two crossed 0.25 inch diameter tubes with sampling holes drilled through the wall in an area-weighted fashion (Fig. 7).

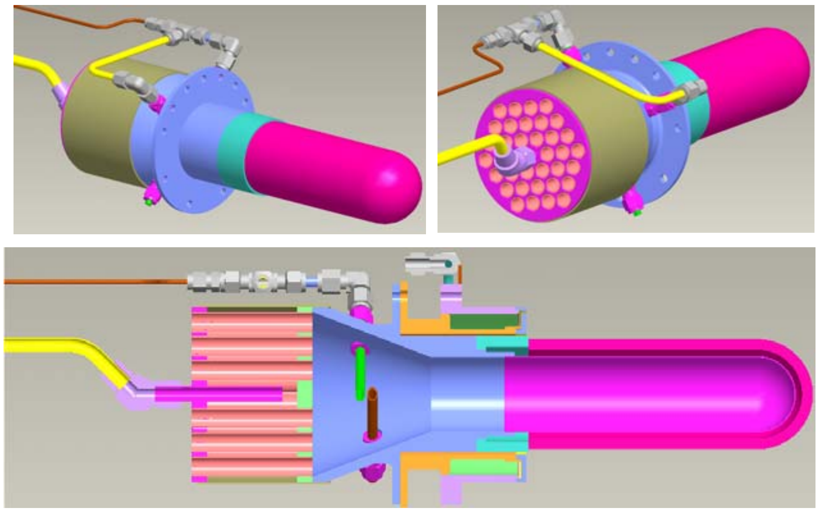

Figure 7. Averaging Rake in Each Burner

In addition, four of the burners were instrumented with additional sampling lines (0.063 inch diameter). These additional lines (up to six per premixer) were used to measure the spatial variation of the fuel/air ratio within each of these four premixers. Inlet flow non-uniformities across the inlet plane of a single burner would be expected to produce a wider variation in fuel/air ratio with that burner. The sampling tubes can be seen inserted into the mixer in Figure 3. Burners equipped with such sampling lines were evenly spaced around the engine. Figure 8 illustrates the location of such burners in the combustor and the results for tests without restrictors.

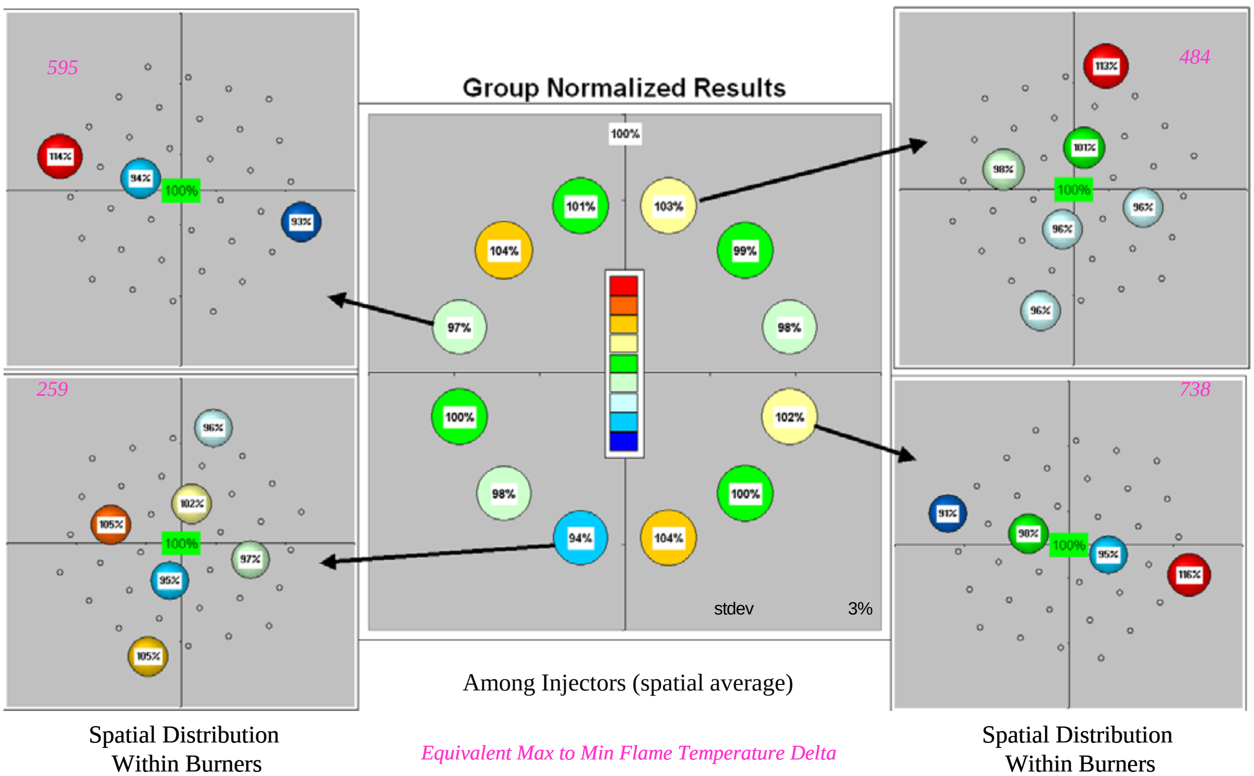


Figure 8. Measurement of Fuel Concentration Distribution: Without Restrictor Plates

Measurements without the restrictor plates installed showed excellent average uniformity among burners, with a standard deviation between rake measurements of only 3%. This is indicative of the careful effective area controls instituted on both the air and fuel passages of each burner. However, the spatial distribution inside each individual burner was not as good. In general, the measurements showed large circumferential discrepancies that resulted in the burners operating hotter on the sides nearest the combustor housing. Similar results were seen in the same type of measurements conducted during the T-70 in-house tests, and this behavior was predicted by CFD analyses (Fig. 1). The large variation in burner surface temperature can explain the degraded stability and higher $NO_x$ emissions observed during the C-40 and T-70 tests.

Figure 9 shows fuel concentration data collected with the restrictor plates installed. A qualitative comparison with Fig. 8 suggests that the internal (spatial) fuel concentration distribution in this situation is more random and not circumferentially biased (but perhaps more radially biased).

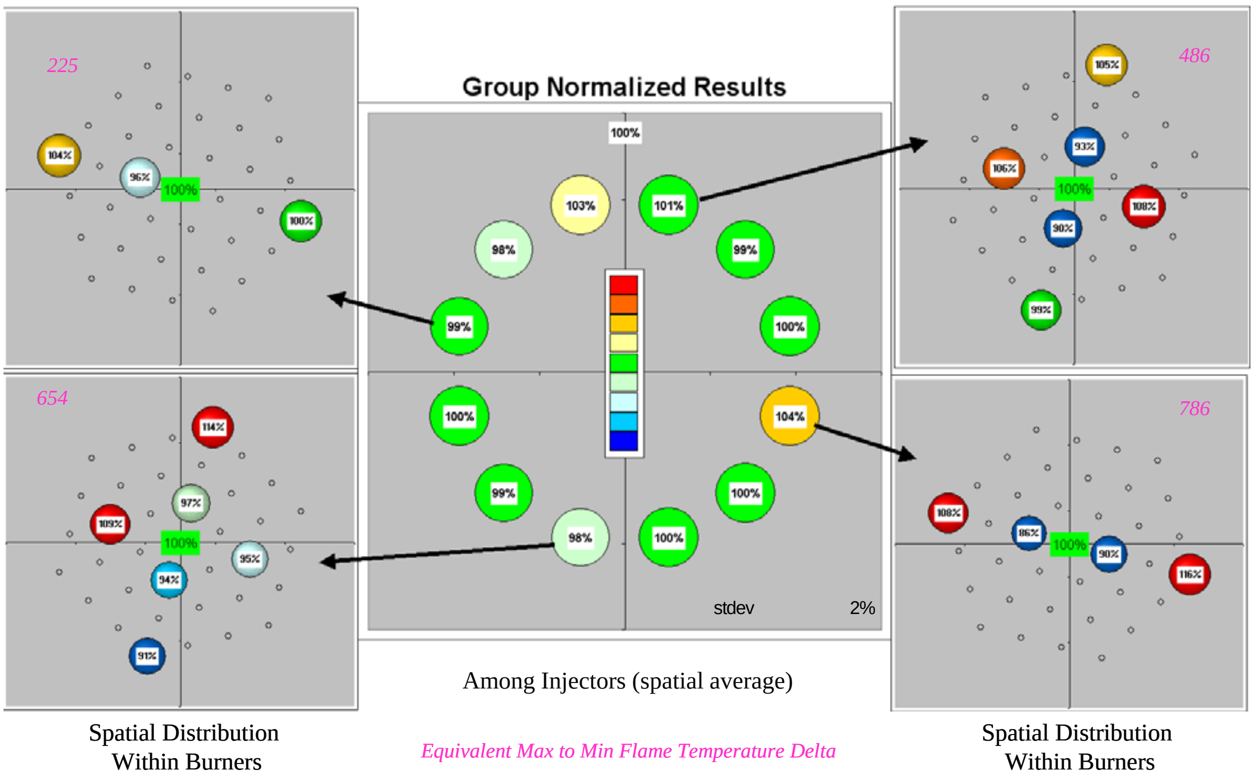


Figure 9. Measurement of Fuel Concentration Distribution: With Restrictor Plates

Previous single burner testing, conducted during internal distributor development, has demonstrated that burner performance is more sensitive to circumferential rather than radial unmixedness. In these tests, the results showed that additional mixing inside the burner (downstream of the premixer) is able to dissipate radially biased fuel concentrations which produces lower $NO_x$ and CO emissions. On the other hand, circumferentially biased profiles are not washed out inside of the burner. Thus, “rich” and “lean ” zones occur on the burner surface. This influences local reaction temperatures and emissions.

The improvements in the premixing levels documented in the second C-40 test resulted in improved emissions and stability. We believe the primary role of the restrictors in the second test was to reduce the magnitude of airflow variations among the burners and across any single premixer. From these interpretations, we conclude that more attention must be focused on improving the airflow distribution into the premixers, both mixer-to-mixer and across any one mixer. This will be approached through more robust premixer inlet design and/or improved compressor discharge flow control upstream of the combustor plenum. This should allow the emissions achieved in the loop testing to be realized with the T-70 engine.

## 5.0 Conclusions

A second round of engine tests of the nanoSTAR™ combustion system was completed successfully. The C-40 loop engine, a recuperated turbine, served as the evaluation vehicle. Ignition, acceleration, and transitions between pilot and main stages were smooth. Control up to full-load engine speed was demonstrated several times, adding confidence to the capability of adapting the surface-stabilized combustion system to real gas turbines.

Performance with and without restrictor plates was compared. Restrictor plates that reduced inlet air non-uniformities improved emissions and stability. $NO_x$ and CO levels below 3 and 15 ppmv (15% $O_2$), respectively, were realized at simulated T-70 engine conditions. These emissions levels were similar to those achieved in single burner tests. In addition, combustion-driven pressure oscillations were not encountered at any point during the tests. The test results support the hypothesis that an improved premixer design that is less sensitive to flow non-uniformities will allow the targeted emission levels to be achieved in the T-70 turbine.